Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 16 August 2001 (MN LaTeX style file v1.4)

Evolution of the Orion Nebula Cluster

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16 August 2001

ABSTRACT
Observations of star formation in the Galaxy support the conclusion that most stars – including our own – form in an environment like the Orion Nebula Cluster (ONC). We construct a range of dynamical models of the ONC, using Aarseth's NBODY6 code, and explore their consequences for the cluster's origins and its subsequent evolution. We find that the most acceptable fits to the cluster density profile are obtained in models where the cluster is set up in virial equilibrium and where the cluster extends well outside the limits of existing photometric surveys. However, current estimates of the virial ratio suggest the cluster is already unbound. We show that the size and age of the ONC in this case implies either that it became unbound only very recently, or else that it has expanded quasi-statically. In the latter case, it's initial central density may have exceeded its current value by $1-2$ orders of magnitude. We stress the importance of future proper motion experiments to distinguish between these possibilities.

Key words: open clusters and associations: individual: Orion Nebula Cluster – celestial mechanics, stellar dynamics

1 INTRODUCTION

Star formation occurs within molecular clouds on a wide range of scales throughout the Galaxy, and with stellar densities varying from 10 to 10^4 stars pc^{-3}. However, the dominant environment (in the sense of being where most stars form) is thought to be at the upper end of this range, typically a dense young cluster embedded within a giant molecular cloud. This is a consequence of the mass distribution function for molecular clouds: there are more low-mass clouds around but most of the mass is found at larger scales (Miller & Scalo 1978; Elmegreen 1985; Clarke, Bonnell & Hillenbrand 2000). As well as forming hundreds or even thousands of ordinary low-mass stars like the Sun, giant molecular clouds usually also form massive O and B type stars. One well-studied example of this environment is the Orion Nebula Cluster (ONC), a nearby star-forming region containing over 4000 stars within a volume five parsecs across. Only a few million years old, it lies about 470 pc away at the edge of the giant molecular cloud in Orion, and appears prominently in the sky as the central star in Orion's sword. The core of the ONC, sometimes called the Trapezium cluster after the four eponymous O and B stars at the very centre, contains about 1000 stars with a peak density of 5×10^4 stars pc^{-3} (McCaughrean & Stauffer 1994; Hillenbrand & Hartmann 1998).

The nature of the ONC and regions like it raises a number of important questions regarding the formation of planetary systems. Compared to conditions in the Solar neighbourhood, the ONC is a violent, crowded place, seemingly quite hostile to the survival of a planetary system. Did the Solar system form in such a place? Or was the Sun one of the minority of stars forming in quieter, less dense regions – in which case should we expect systems like our own to be rare? Observations of the ONC do suggest that the majority of stars there have circumstellar disks (Hillenbrand et al. 1998; Lada et al. 2000; Rebull et al. 2000). What kind of planetary systems, if any, will these produce?

Recent attempts to understand the impact on planet formation of stellar encounters and UV photevaporation in the ONC have concluded that the cluster's dynamics are a critical factor (Scally & Clarke in press; Bonnell et al. 2001). However, the dynamics of the ONC are difficult to establish, and despite its popularity as an observational target they remain poorly understood. In this paper we address the problem by constructing a range of dynamical N-body models and comparing them to observations of the present-day cluster. We are concerned primarily with such gross features as its energetics – to what degree the ONC is bound or unbound – and its large-scale density distribution. A companion paper (Scally & Clarke, submitted) addresses the issue of possible substructure in the formation of the cluster.

In the following section we review the current state of our observational knowledge of the cluster and its physical parameters, and in Section 3 we then describe how these are represented in our N-body models. Then in Sections 4–6 we consider in turn models starting from virial equilibrium, unbound models, and cold collapse models. In Section 7 we discuss these their consequences for the origins of the ONC, its fate, and the birthplace of the Solar system.

2 COMPOSITION AND DYNAMICS OF THE ONC

Although the ONC is relatively close, the large amounts of gas and dust present and the bright emission from the Trapezium stars and H II nebulosity have until recently hidden much of its population, and prevented us from accurately measuring its kinematics. Photographic studies have also been further hampered in the past by the intrinsic redness of the low-mass stellar population there. Recent technological advances, however, have made it possible to get around some of these difficulties, and to greatly improve our understanding of the cluster's size and composition. Herbig & Terndrup (1986), for example, used a CCD with a narrow band filter to reduce the effect of nebulosity in observing the Trapezium, and McCaughrean & Stauffer (1994) used adaptive optical techniques in the infrared to survey the cluster's central $0.2 \times 0.2\,\mathrm{pc}^2$. The past decade has also seen a number of deep and high resolution studies at optical wavelengths using the *Hubble Space Telescope* (e.g. Prosser et al. 1994; O'Dell & Won 1996; Bally et al. 1998; Bally, O'Dell & McCaughrean 2000).

Membership: The existence of a small population of faint low mass stars surrounding the Trapezium was first noted by Trumpler in 1931. Since then the census has grown with each new set of observations, and the most recent survey of the whole cluster (Hillenbrand & Hartmann 1998) detected 3500 stars down to mass $0.1\,\mathrm{M}_\odot$ within 2.5 pc of its centre. A subsequent survey of the central $0.7 \times 0.7\,\mathrm{pc}^2$ (Hillenbrand & Carpenter 2000) down to mass $0.02\,\mathrm{M}_\odot$ increased the star count in that region by 20 per cent. We can therefore estimate a population of 4000 stars for the cluster as a whole, though the true population may be higher still. Kroupa (2000) speculates that the ONC may contain as many as 10,000 stars, with over half of them at present either hidden in binary systems, obscured by gas, or lying outside the regions surveyed.

Shape and surrounding structure: Fitting ellipses to the (projected) stellar distribution, Hillenbrand & Hartmann (1998) found a deviation from circularity in the cluster, increasing towards its edge, from an eccentricity of ~ 0.3 at 0.1 pc to ~ 0.5 at 1 pc. On even larger scales, the ONC seems to be part of a linear structure, an arc or filament of stars about 15–20 pc in length running roughly north-south in the sky (i.e. along the northern half of the Orion A cloud). For example see Figure 7 of Jones & Walker (1988), which plots data from Parsamian & Chavira (1982), or Figure 2 of Nakano, Wiramihardja & Kogure (1995). Also the survey of Rebull et al. (2000), which found a higher density of stars in flanking fields to the north and south of the ONC than to the west. It is uncertain, however, whether there is any dynamical relationship between the ONC and other parts of this structure – whether, for example, the ONC represents a knot or condensation along a previously collapsed filament.

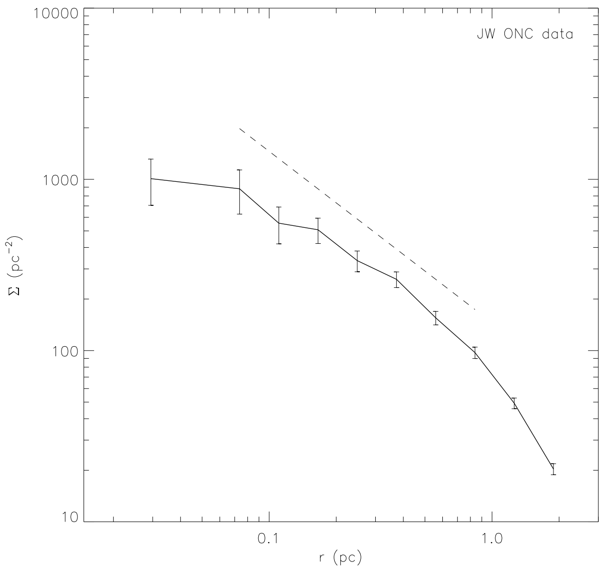

Figure 1. Projected density profile of the ONC as seen by Jones & Walker (1988). The dashed line has a slope of -1 (corresponding to $1/r^2$ in three dimensions).

Density profile and substructure: Figure 1 shows the projected density profile of the ONC as seen by Jones & Walker (1988). A similar profile was plotted by Hillenbrand & Hartmann (1998) for their data. Over most of the cluster the density appears to go as $1/r^2$ ($1/r$ in projection), with a flat core about 0.1 pc in radius.* The half mass radius of the cluster, R_h, lies at about 1 pc. More than anything else, this density distribution resembles that of a relaxed system in equilibrium, such as an isothermal sphere (e.g. Binney & Tremaine 1987). Indeed, Hillenbrand & Hartmann (1998) obtained a good fit to their data using a King model, and Figure 2 shows the same model compared with the data from Jones & Walker (1988) (and scaled accordingly). King models are normally used in modelling globular clusters – systems very much older than the ONC – as we discuss in Section 4.

Mass: Almost all recent surveys of the ONC have found an overall mass spectrum similar to that of the Galactic field, differing only with regard to the lower limit and the population of low mass stars. Hillenbrand's (1997) survey originally found a mean mass of 0.8 $\mathrm{M}_\odot$ and detected almost no stars below 0.1 $\mathrm{M}_\odot$. As noted above, however, this limit has now been extended to 0.02 $\mathrm{M}_\odot$ in the centre of the cluster by Hillenbrand & Carpenter (2000). If repeated throughout the cluster, this would bring the mean mass down to around $0.5\,\mathrm{M}_\odot$, in line with the recent theoretical mass function of Kroupa, Tout & Gilmore (1993). The total mass of the cluster thus appears to be about 2000 $\mathrm{M}_\odot$.

It is not clear how much mass is still present in the form of gas. Unless the star forming efficiency of the cluster was very high, there must have been a considerable amount there

* Henney & Arthur (1998) have found evidence for a further peak in clustering within 0.02 pc of θ^1C Ori.

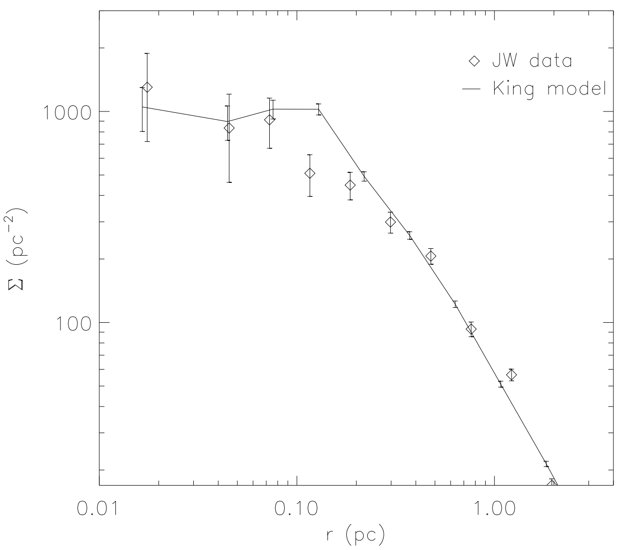

Figure 2. Projected density profile of the ONC as seen by Jones & Walker (1988) with the King model fit of Hillenbrand & Hartmann (1998) scaled accordingly.

initially, but radiation pressure from the massive Trapezium stars may well have cleared most of it by now. A radio map of hydrogen gas by Wilson et al. (1997) found evidence for the escape of ionized gas from the centre of the cluster, in the direction away from the background cloud. There is no clear consensus, however, as to how much (or how little) gas remains, even in the central region. Most models assume that in the centre at least, the stellar wind from θ^1C Ori has blown a cavity of highly shocked material. See O'Dell (in press) for a survey of the nebular structure (M42) surrounding the ONC.

Age: Data from Hillenbrand (1997) and Hillenbrand & Carpenter (2000) suggest that about 80 per cent of stars in the ONC are less than 2 Myr old (with a mean age of ~ 0.8 Myr). A more recent study by Palla & Stahler (1999) agrees with this result, and adds that star formation seems to have started there perhaps 10 Myr ago, growing slowly at first and accelerating to peak in the last million years. However, it is important to bear in mind that accurate ages are difficult to establish for young stars, being dependent on a number of observational factors which are hard to constrain. A recent survey by Hartmann (2001) of the difficulties involved concluded that most estimates of the ages of young stars are accurate to no more than a factor of 1.6–2.

Proper motions: Jones & Walker (1988) used a series of optical wavelength photographic plates taken over a baseline of about 20 years, and obtained proper-motion measurements for over 1000 stars in the ONC. Compared to the deeper and higher spatial resolution surveys of Prosser et al. (1994) and McCaughrean & Stauffer (1994), their data reveal only a fraction of the total stellar population. However, it remains the best proper-motion survey to date, and covers a relatively large area on the sky, extending roughly 15 arcmin (2 pc) from the cluster centre. Over most of the cluster, Jones & Walker measured a three-dimensional velocity dispersion $\sigma = 4.3 \pm 0.5\,\mathrm{km\,s^{-1}}$, with slight evidence for an increase towards the core. There was also some indication of anisotropy in the dispersion towards the outer regions of the cluster, increasing in the radial direction (the direction towards and away from the cluster centre) and decreasing in the tangential direction. The errors, however, in the dispersions at the survey edge are large ($\sim 1\,\mathrm{km\,s^{-1}}$).

An important caveat to the Jones & Walker value for the velocity dispersion is that it is actually a lower limit, as the process of data reduction was such that any effect of rotation or expansion in the cluster would have been excluded from the reduced velocity data. This is discussed further in Section 5.1. For the time being, with no obvious way to correct for an unknown expansion velocity, we will take it at face value. Combined with the half-mass radius $R_\mathrm{h} = 1\,\mathrm{pc}$, it gives a crossing time for the cluster of

$$T_\mathrm{c} = \frac{2R_\mathrm{h}}{\sigma} \approx 0.5\,\mathrm{Myr} \tag{1}$$

The crossing time is a useful measure of the rate of dynamical evolution in a stellar system, and we conclude that the ONC seems to be dynamically young – only a few crossing times old.

Virial ratio and possible expansion: Assuming a total mass $M = 2000\,\mathrm{M_\odot}$, and estimating the cluster's kinetic energy $K = \frac{1}{2}M\sigma^2$ and potential energy $W = GM^2/2R_\mathrm{h}$, we can express the boundedness of the cluster by the virial ratio

$$Q = \frac{K}{W} = \frac{R_\mathrm{h}\sigma^2}{GM} \approx 1.5 \tag{2}$$

Some authors have concluded from this that either the ONC must be unbound and expanding, or there must be a significant amount of gas or stars – perhaps low-mass binary companions – present and not seen, to keep it bound (Jones & Walker 1988; Tian et al. 1996; Hillenbrand & Hartmann 1998; Kroupa 2000). However, reasonable errors in the observational parameters can easily account for an error of over 50 per cent in this calculation.

3 SIMULATION SETUP

Our goal in this paper is to construct dynamical models of the ONC and match them to its present day appearance. The observational evidence is somewhat contradictory, since as we have seen the kinematical data of Jones & Walker (1988) suggest an unbound cluster, while its appearance is very much that of a relaxed system in equilibrium. We will consider both bound and unbound models, modelling the cluster as an isolated system consisting solely of stars, with no gas or background potential. This means that when considering bound models we ignore the velocity dispersion

However, in all cases we require that if a model is to be considered a satisfactory match to the ONC, it must have the correct population, mass function and density profile at the ONC's age (even though the latter is not extremely well constrained).

3.1 Population

In some N-body applications, matching the population of the physical system causes problems, as a large number of particles can make the calculation prohibitively slow, but fortunately that is not the case here. Simulations of several thousand stars, running for many tens of crossing times, are well within our reach without needing to use specialised or purpose-built hardware.†

3.2 Mass function

It has been shown in a number of previous studies (Terlevich 1987; Giersz & Heggie 1996; de la Fuente Marcos 1995) that the existence of a spectrum of masses affects the dynamics of a star cluster, speeding up its evolution in comparison with a cluster whose stars all have the same mass. The specific choice of mass function used (whether a simple power law or a more complicated function) seems to be important only for small-N clusters, where it can have a measurable affect on the evolution rate. For clusters containing more than about 500 stars, the differences become insignificant, and what matters is simply the existence of a range of masses (de la Fuente Marcos 1995).

For this reason, and because the observational data for the ONC is somewhat noisy, the choice of which mass function to use in generating stellar masses for our simulation is not critical. We choose one which is the result of recent work, namely that of Kroupa et al. (1993). This is a combination of three power laws, including more very low mass ($< 0.5\,\mathrm{M}_\odot$) stars than previous functions (e.g. Scalo 1986), and provides a reasonable fit to the ONC data. Using this function we generate masses in the mass range 0.1–50 $\mathrm{M}_\odot$.‡ It should be pointed out that drawing 4000 masses at random from this distribution very rarely produces a star as massive as 50 $\mathrm{M}_\odot$(the mass of θ^1C Ori). More commonly the most massive star in the cluster is 20–30 $\mathrm{M}_\odot$. However, provided it is greater than 20 $\mathrm{M}_\odot$, the dynamical influence of the most massive star on the rest of the cluster is much the same.

3.3 Velocity distribution

Once the stellar positions have been generated, velocities are generated isotropically for the stars, drawn from a Maxwell-Boltzmann distribution. The velocity of each star is then scaled by a global constant to achieve the desired virial ratio.

Like the mass function, the actual form of the velocity distribution is not dynamically critical unless it is significantly far from an equilibrium distribution. In our simulations we expect the equilibrium distribution to be not far from Maxwell-Boltzmann, perhaps with the dispersion ($\sigma = \sqrt{\overline{v^2}}$) varying with radius (as seen in a King model for example). The available observational data are not sufficiently accurate to determine the form of the distribution function in the ONC, and the only instance in which the velocity distribution influences the density profile is in the case of a highly unbound cluster, as we will discuss in Section 5.

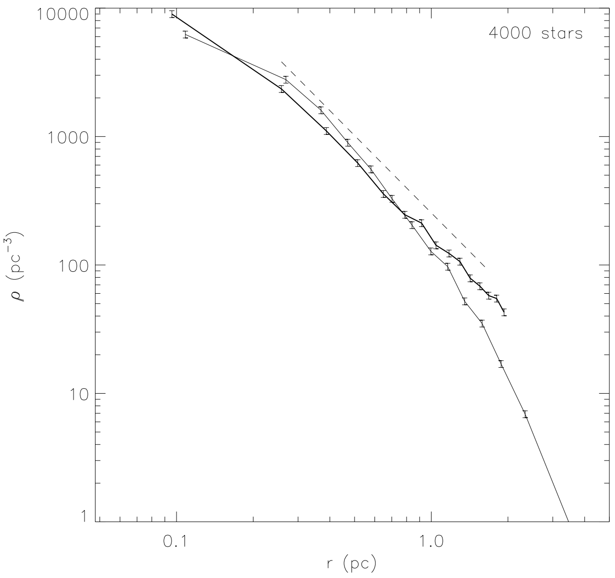

Figure 3. Evolution of a $1/r^2$ density distribution with a finite radius, in three dimensions, for a cluster of 4000 stars starting in virial equilibrium. The initial density profile is represented by the thicker line. Subsequently it flattens in the centre to form a core, and falls off in the outer reaches of the cluster due to the smoothing-out of the edge. Note that the resulting density profile is steeper than $1/r^2$ (marked by the dashed line) over most of the cluster.

4 EVOLUTION IN VIRIAL EQUILIBRIUM

We employ two different initial density distributions, one uniform (ρ constant) and one with $\rho = \rho_0/r^2$. In both cases the stars are generated within a finite radius, so that unlike the ONC, whose boundary is uncertain and probably not well defined, the boundary of our simulated clusters at $t = 0$ is sharp. During the cluster's subsequent evolution, this boundary will become diffuse, and the density will drop towards the edge – even if the cluster starts in virial equilibrium.§ Figure 3 shows this effect in a cluster which starts off in virial equilibrium with a $1/r^2$ density profile. There is some slight evidence for a fall-off in the projected density profile of the ONC as well, as is shown in Figure 4, but it is not as severe as in our simulations. (Note that we use the Jones & Walker (1988) data to represent the density profile of the ONC, assuming that their population of stars faithfully samples the distribution of the cluster as a whole over the region surveyed. Supporting this assumption is the fact that there is no significant difference between the

† A typical run with NBODY6 following 4000 stars in virial equilibrium for 30 crossing times takes a day or two at most on a typical (e.g. 400 MHz) RISC CPU.

‡ Extending the lower limit has a negligible effect on the cluster dynamics.

§ This is not to be confused with the projection effect of a boundary, which causes a similar deviation in projected density profile but which is only significant at the very edge. We ignore this effect here.

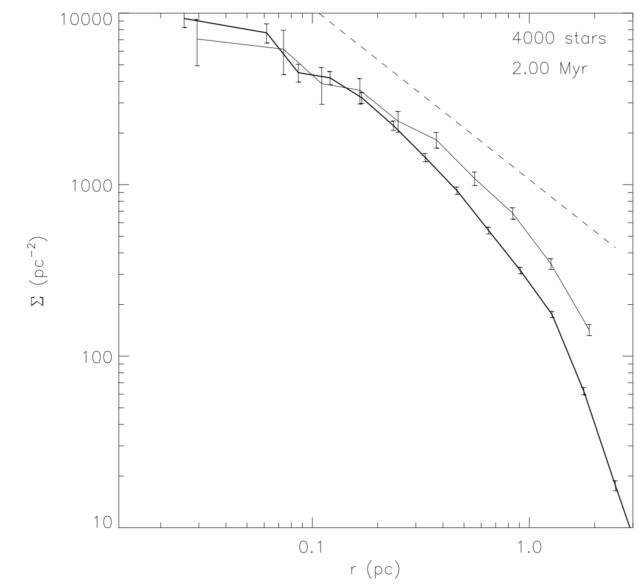

Figure 4. Projected density profile of a simulation of 4000 stars after 2 Myr (thick line) compared to that of the Jones & Walker (1988) survey of the ONC (thin line, scaled so that the core density matches that of the simulation). The cluster was initialised with a $1/r^2$ density distribution in virial equilibrium. The dashed line has a slope of -1 (corresponding to $1/r^2$ in three dimensions).

Jones & Walker density profile and that of the much more complete survey by Hillenbrand & Hartmann (1998).)

This evolution in density is due to the fact that although our initial conditions may have a virial ratio of 0.5, they do not represent a steady-state solution of the collisionless Boltzmann equation, (the fundamental equation of stellar dynamics). One steady-state solution of this equation which is physically plausible is the King model, in which the density is finite at all points and falls to zero at a finite radius, called the *tidal radius*, $R_{\rm t}$.

In the King model shown in Section 2 (providing a good fit to the ONC) the density profile is close to $1/r^2$ and the model is very similar to an isothermal sphere over the region shown. The crucial difference between this and the simulations we have set up is that the King model extends out to very low densities, rather than stopping abruptly at some intermediate density. Most of the models we generate for NBODY6 terminate at $r \approx 10r_0$, where r_0 is the core radius, while the King model continues out to $R_{\rm t} \approx 100r_0$. If we use a dynamical King model for our initial conditions, we find the density profile does indeed remain stable over the timescale of several crossing times. (Over a much longer timescale the effect of collisions become important and the evolution can no longer be described by the collisionless Boltzmann equation.)

However, there are a number of reasons why we do not expect the dynamics of the ONC to be truly those of a King model. The particular King model fit required has a tidal radius $R_{\rm t} \approx 20$ pc, far larger than is plausible for the ONC. On this scale the structure of the Orion A cloud and the stellar distribution (as revealed for example by surveys of Hα emission line stars in Parsamian & Chavira (1982) and Nakano et al. (1995)) is far more linear than spherical. Such a cluster would also contain about 30,000 stars.

Furthermore, those astrophysical systems that do fit King models, like globular clusters and elliptical galaxies, are typically hundreds of crossing times old. A King model is a very specific dynamical equilibrium, and for the ONC, only a few crossing times old, to have started in that state (or even very close to it) would seem an improbable coincidence.

In simulating the ONC, therefore, we will not use King models. Instead we will stick to clusters having only 4000 stars and a radius of about 2 pc. For the purposes of deciding when a particular model matches the ONC, we consider a fit like that shown in Figure 4 to be satisfactory, even though the model density profile deviates more from $1/r^2$ than the ONC data.

4.1 Uniform initial density

Models starting with a uniform density profile must clearly relax to a centrally condensed profile before they can be considered a match to the ONC. Ultimately, these models should approach the same dynamical equilibrium as those starting with a $1/r^2$ profile, but over the timescale of a few crossing times the two cases are normally quite different, with initially uniform models tending to have a much larger flat core. Figure 5 shows how an initially uniform cluster of 4000 stars compares to the Jones & Walker (1988) ONC data, for two radial scalings: one in which the initial cluster radius matches that of the ONC (~ 2 pc), and the other in which the core density is scaled to match that of the $1/r^2$ case. In virial equilibrium, initially uniform models do not produce a good fit to the ONC. We will nevertheless consider them again in Section 6, when we discuss models undergoing a collapse from cold initial conditions.

5 UNBOUND CLUSTERS

We have seen that a cluster formed in virial equilibrium with a $1/r^2$ density distribution soon establishes a core, and thereafter roughly matches the ONC in appearance (Figure 3). However, we have also seen that observations of the mass in stars present and of the cluster's velocity dispersion suggest that it is not in virial equilibrium. Without incorporating something like a gas potential or extra stars, a virial equilibrium model cannot be a realistic simulation of the ONC, unless the virial ratio calculated from observations is wrong by at least a factor of two.

Suppose then that the ONC is unbound, perhaps as a result of having lost a large amount of gas since formation. Unless this has only just occurred and there has not yet been time to react, the cluster should now be expanding. We mentioned in Section 2 that observations of proper motions are unable to detect expansion or contraction in the cluster due to the way the data is reduced, and will examine the consequences of this again later in this section. First, however, we consider the implications for the density profile and age of the ONC if it is unbound.

The models presented in this section are all initialised with a virial ratio greater than unity We will compare our expanding clusters with the following simple model. At the

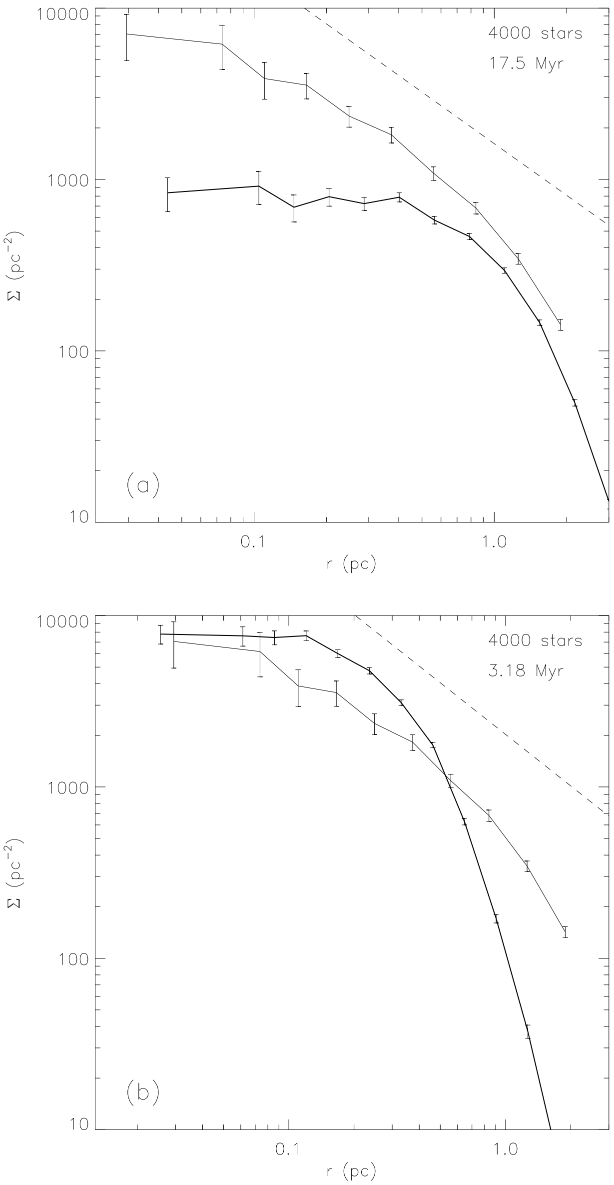

Figure 5. Projected density profile of a simulation of 4000 stars (thick line) compared to that of the ONC (thin line). The cluster was initialised with a uniform density distribution in virial equilibrium. The solid line has a slope of -1, and the dashed line marks the half mass radius for these stars. The scaling of the model in (a) is such that the initial cluster radius is 2 pc, while in (b) it is scaled so that the model core density matches that of the ONC.

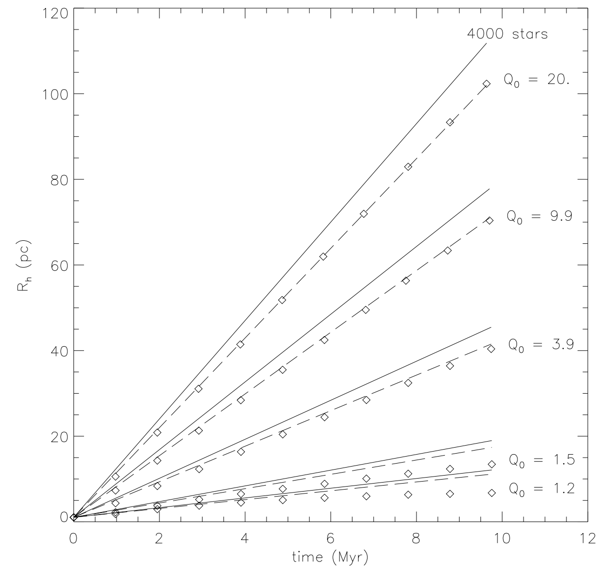

Figure 6. Expansion of $R_{\rm h}$ for clusters with a range of values of Q_0, showing the fit to the linear expansion model described in the text. The solid line in each case shows expansion with the median velocity $v_{\rm m}$, while the dashed line has a slightly reduced velocity of $0.92\,v_{\rm m}$, giving a better fit.

start of the expansion, the cluster has half mass radius $R_{\rm h0}$ and velocity dispersion σ_0, so that its initial virial ratio

$$Q_0 = \frac{R_{\rm h0}\sigma_0^2}{GM} \qquad (3)$$

At some subsequent time, the cluster expands to a half-mass radius $R_{\rm h}$ with velocity dispersion σ, and energy conservation gives

$$\frac{1}{2}M\sigma_0^2 - \frac{GM}{2R_{\rm h0}} = \frac{1}{2}M\sigma^2 - \frac{GM}{2R_{\rm h}}$$

$$\sigma^2 = GM\left(\frac{Q_0-1}{R_{\rm h0}} + \frac{1}{R_{\rm h}}\right)$$

(from (3)). As $t \longrightarrow \infty$, $1/R_{\rm h} \longrightarrow 0$ and so

$$\sigma_\infty = \sqrt{\frac{GM}{R_{\rm h0}}(Q_0-1)} \qquad (4)$$

We assume that the cluster expands at a rate proportional to this (asymptotic) velocity. A short while into the expansion the stars will become ordered in radius according to their initial velocities, and within the half mass radius at any given time we expect to find all stars with initial speeds less than the median $v_{\rm m}$ of the initial velocity distribution.¶ The half mass radius itself should expand at a rate equal to $v_{\rm m}$. In a Maxwellian distribution, $v_{\rm m} \approx 0.89\,\sigma$. Thus at any time t,

$$R_{\rm h} = R_{\rm h0} + 0.89\sqrt{\frac{GM}{R_{\rm h0}}(Q_0-1)}\;t \qquad (5)$$

Figure 6 shows the expansion of $R_{\rm h}$ with time for several initial virial ratios. Our model, which we will refer to as the asymptotic expansion model, agrees fairly well for $Q_0 \gtrsim 4$, and very well if one allows a small adjustment of the expansion velocity σ_∞ (by less than 10 per cent). For values of Q_0 closer to unity, however, the expansion is slower than the model predicts – even over long timescales, as Figure 7 shows. Indeed, for $Q_0 \lesssim 1.2$ the expansion even halts for a period, implying that many of the stars within $R_{\rm h}$ are in fact bound, despite the fact that $Q > 1$ globally.

Figure 8 shows the fraction $f_{\rm bound}$ of stars which are bound – that is, whose kinetic energy is less than the po-

¶ There is no mass segregation in the initial configuration so $R_{\rm h} = R_{N/2}$.

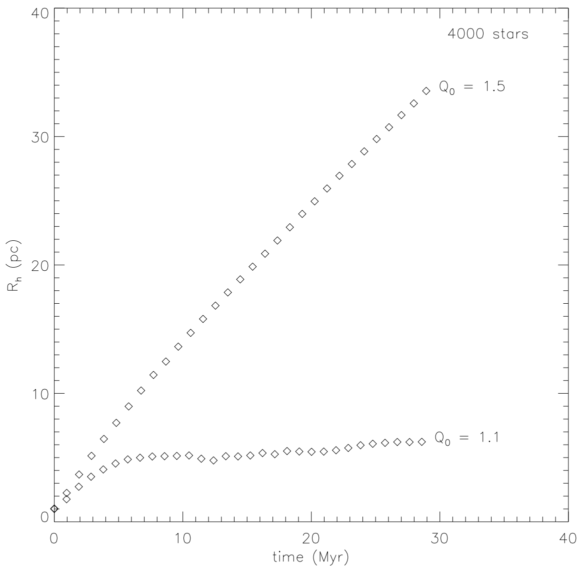

Figure 7. Expansion of $R_{\rm h}$ for clusters with $Q_0 = 1.5$ and 1.1.

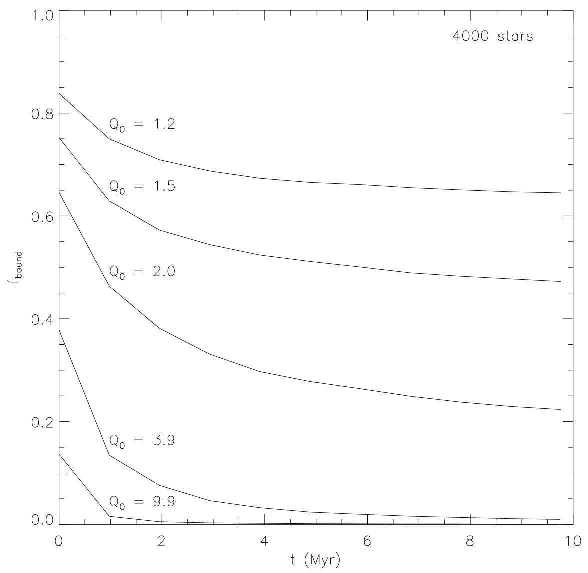

Figure 8. Fraction of stars which are bound, evolving with time for several values of the initial virial ratio, Q_0.

tential energy due to all the other stars in the cluster – and how this varies with time for several values of Q_0. Note that the initial value of $f_{\rm bound}$ in each case can be estimated analytically by integrating the Maxwell distribution from $v = 0$ to $\sqrt{\overline{v_{\rm esc}^2}}$, the root mean squared escape velocity. For any density distribution the latter is given by

$$\overline{v_{\rm esc}^2} = \frac{4W}{M} = \frac{2\sigma^2}{Q} \tag{6}$$

(See e.g. Spitzer (1940).) For comparison, here is a table giving $f_{\rm bound}$ estimated in this way for several values of Q_0:

Q_0	0.5	1.0	1.2	1.5	2.0	4.0	10.0
$f_{\rm bound}$	0.99	0.89	0.83	0.74	0.61	0.32	0.10

As Figure 8 shows, the bound fraction falls away from these initial values as the clusters evolve. As the cluster as a whole becomes less bound, a bound component is left behind whose size is determined by Q_0.

We can consider Q_0 in terms of a *star formation efficiency* ε by noting that if the cluster is initially in virial equilibrium with a mass $M_{\rm stars}$ of stars and $M_{\rm gas}$ of gas, so that

$$\varepsilon = \frac{M_{\rm stars}}{M_{\rm stars} + M_{\rm gas}} \tag{7}$$

then if the gas is instantaneously removed, the virial ratio will become

$$Q_0 = \frac{1}{2\varepsilon} \tag{8}$$

Kroupa, Aarseth & Hurley (2001) found that in clusters with $\varepsilon \approx 0.3$ where the gas is removed in less than a crossing time, about one third of the stars remain in a bound component. This is a little less than the fraction of ~ 0.45 which seem to be left for $Q_0 = 1.5$ in Figure 8, but their simulations also included the effects of stellar evolution and an external tidal field, which contribute to the removal of stars from the system. Adams (2000) constructed models of gas expulsion in which between 45 per cent and 60 per cent of stars remain bound for $\varepsilon \approx 0.3$. In essence his approach was similar to that discussed above in estimating $f_{\rm bound}$ from the distribution function. However, as pointed out by Geyer & Burkert (in press), his models are not strictly analogous to the initial conditions considered here, since he considered the removal of a gas component extending outside the stellar distribution, which means that the effective value of ε in the stellar region is higher than that of the model as a whole.

In Geyer & Burkert's own calculations, no bound component is left for any value of ε less than 0.3, and their results show a dramatic decline in $f_{\rm bound}$ from 0.9 to 0.2 as ε goes from 0.6 to 0.4. In our models the same decline occurs over a broader range, roughly $\varepsilon = 0.6$–0.25 ($Q_0 = 0.83$–2.0). Kroupa et al. (2001) ascribe the discrepancy between their results and those of Geyer & Burkert (in press) to the fact that the latter calculations used a collisionless N-body code, and propose that two-body interactions between stars have hindered the dissolution of their $\varepsilon = 0.3$ model.

The dynamics and density profile of a bound remnant are essentially those of a cluster in virial equilibrium, so in principle we could consider them as suitable models for the ONC, similar to the virial equilibrium models discussed previously. The density profile shown in Figure 9 is a reasonable fit to that of the ONC in the inner 2 pc, with the dip in the profile just inside 1 pc providing evidence for the growth of a bound core. As time progresses this core increases in size and membership, and eventually (after several million years) is left behind by the unbound stars. The remnant then contains about half the initial number of stars, in a volume eight times the initial volume – a sixteenfold change in density. Note that the slope of the profile is almost entirely an artefact of the initial conditions, since the cluster started with a $1/r^2$ density distribution, and there has been very little dynamical evolution in this system other than an

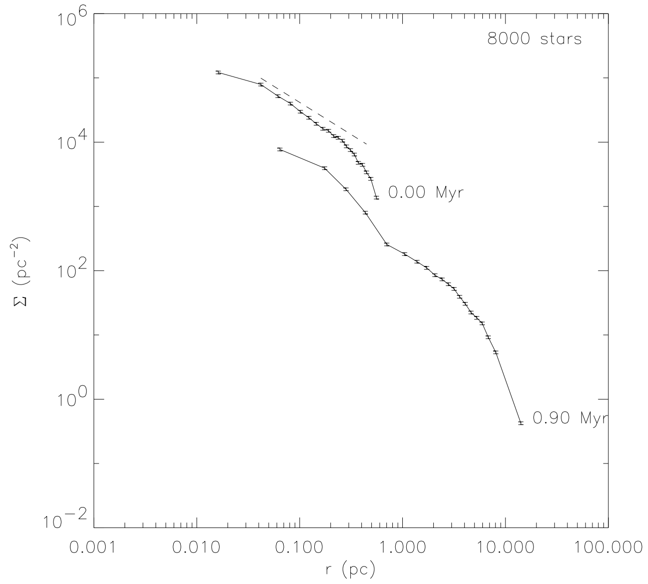

Figure 9. Radial density profile of 8000 stars with $Q_0 = 1.5$ initially and after 0.9 Myr.

expansion.[‖] The bound remnant in this case contains almost 4000 stars (we started with 8000), so apart from the presence at an early stage of an additional 4000 unbound stars, this model is dynamically equivalent to the case of virial equilibrium that we considered earlier.

The more unbound cases ($Q \gtrsim 4$) can be scaled to fit the ONC, and if the initial density profile goes as $1/r^2$ the subsequent fits are even better matches to the ONC since the bound components are smaller. However, it is impossible to find a case which takes more than 0.5 Myr to reach the ONC's present size, and most are much younger, regardless of the initial size. This can be accounted for by the linear expansion model presented above. For a given value of $R_{\rm h}$ (in this case 1 pc) and a given initial Q_0, we have

$$t = \alpha\sqrt{R_{\rm h0}}(R_{\rm h} - R_{\rm h0}) \tag{9}$$

where α is a constant, e.g. $(0.89\sqrt{GM(Q_0-1)})^{-1}$ as derived above. Thus

$$\frac{{\rm d}t}{{\rm d}R_{\rm h0}} = \alpha\left(\frac{R_{\rm h}}{2\sqrt{R_{\rm h0}}} - \frac{3}{2}\sqrt{R_{\rm h0}}\right) \tag{10}$$

and so the maximum value of t for a given $R_{\rm h}$ and Q_0 occurs when $R_{\rm h0} = R_{\rm h}/3$:

$$t_{\rm max} = \alpha R_{\rm h}^{3/2}\left(\frac{1}{\sqrt{3}} - \frac{1}{3}\right) \tag{11}$$

Rearranging this and taking $\alpha = (0.89\sqrt{GM(Q_0-1)})^{-1}$ gives an upper limit on Q_0 for any age t:

$$Q_0 \lesssim \frac{1}{GM}\left(\frac{R_{\rm h}^{3/2}}{0.89\,t}\left(\frac{1}{\sqrt{3}} - \frac{1}{3}\right)\right)^2 + 1 \tag{12}$$

Qualitatively, what happens is that for a given value of Q_0, small values of $R_{\rm h0}$ make σ_0 too high, and the expansion is too rapid. For large values of $R_{\rm h0}$ the reduced expansion rate is outweighed by the fact that the cluster starts too close to its present-day $R_{\rm h}$, and again gets there too soon. The balance (in terms of maximum time to reach a given $R_{\rm h}$) is achieved at $R_{\rm h0} = R_{\rm h}/3$.

For $R_{\rm h} = 1\,{\rm pc}$, $M = 2000\,{\rm M}_\odot$, and $t = 0.5\,{\rm Myr}$, we find $Q_0 \lesssim 2.0$ in (12). But such an age for the ONC would generally be considered to be an absolute minimum; a more realistic age of $\sim 1\,{\rm Myr}$ limits us to even smaller values of Q_0.

Unbound models are potentially interesting as they allow the cluster to have had a much greater density in the past than we see today, which would have important implications for disk-disrupting encounters and photoevaporation by massive stars. However, it seems that the only plausible unbound models for the ONC are the marginal cases in which $1.0 \lesssim Q_0 \lesssim 2.0$, where the system as a whole contains up to twice as many stars as we observe within the central 2 pc, and where the bound component has not had time to become distinct. Even within these constraints the fit is not superb, being essentially a superposition of bound and unbound components. In the absence of subclustering then, there is thus only a small range of initial conditions which allow the ONC to have had a significantly greater density in the past than it has today. (Subclustering, considered by Scally & Clarke (submitted), enables us to consider a collection of dense subgroups which rapidly expand and merge.)

There is an important caveat to this. In terms of star formation efficiency, we have considered models in which expansion is triggered by an *instantaneous* expulsion of gas from the cluster. Clearly this need not be the case, and if the gas expulsion proceeds at a sufficiently slow rate, taking many crossing times, the cluster can expand while maintaining its equilibrium along the way. Geyer & Burkert (in press) have found that much higher bound fractions are left behind when the gas expulsion is slowed down. In this way it may be possible to begin with greater densities and still end up with a cluster like the ONC which is not far from virial equilibrium.

To investigate this we need a code which can include the influence of a time-varying potential (to represent gas leaving the cluster). NBODY6 in its normal form cannot do this, but Kroupa has written an extended version which can – the first results from which are presented in Kroupa et al. (2001). (However, the simulations presented in that paper do involve gas expulsion in less than a crossing time, which is why the results are comparable with our pure N-body simulations.)

5.1 Matching Jones & Walker's virial ratio

As we have already mentioned, one major motivation for considering unbound models for the ONC is the measurement by Jones & Walker (1988) of a high velocity dispersion in their proper motion data. Taken as it is, we have seen that their value of σ, $4\,{\rm km\,s^{-1}}$, implies a virial ratio

‖ In the long run we expect the density profile of a highly unbound system (neglecting any bound remnant) to be mapped from its initial velocity distribution, since ultimately $r \approx vt$ for each star. Thus an initial velocity distribution uniform in v (say) would produce a density distribution uniform in r.

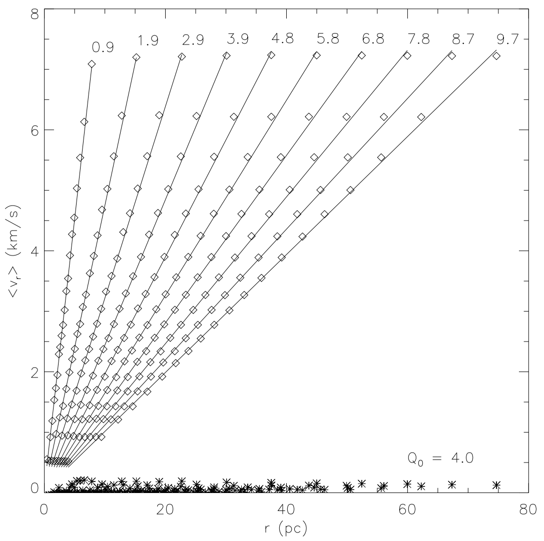

Figure 10. Average radial velocity as a function of radius for an ubound cluster ($Q_0 = 4.0$), evolving over time. At each time (given in Myr), the line is a fit showing the effective correction applied in reducing the data to remove expansion, and the profiles before and after correction are shown by diamonds and stars respectively. (The reduced data points for each time are superimposed but it is clear that the radial velocity is much less than $1\,\mathrm{km\,s^{-1}}$ at all times throughout the cluster.)

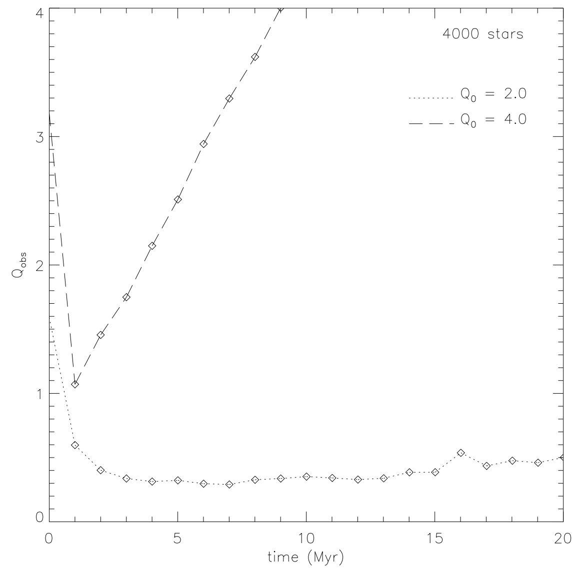

Figure 11. Evolution of the reduced observational virial ratio with time for the cases $Q_0 = 2.0$ and 4.0.

$Q = 1.5$ (Section 2). However, the process of data reduction by which Jones & Walker obtained their proper motions was such that any effects of overall expansion, contraction, or rotation were removed from the data.

The data was compiled from photographic plates taken over a baseline of more than twenty years, and it was necessary to counter the effect of variation in the position of each photographic plate along the focal axis (or rotation in the focal plane). To this end, a linear global scale factor was applied to the measures on each plate so that the root mean squared difference between the radial position (r) of each star as measured on the plate and its position at some reference epoch was minimised. These positions were measured from the plate centre, close to θ^1C Ori (but since the scale factor applied was linear, the point chosen for the origin is arbitrary). The resulting effect on radial velocities would have been to reduce them by a factor proportional to r.

In other words, if the cluster were expanding in such a way that the radial (expansion) velocity of each star was proportional to its radius in the cluster, it would be indistinguishable from a systematic change in the position of the plate, and as such would have been 'reduced' out of the data. Unfortunately, as Figure 10 shows, such a relationship between radial velocity and radius is exactly what one would expect in a freely-expanding cluster. The velocity dispersion would be correspondingly reduced, and we have no way of knowing what the true velocity dispersion of the ONC is – except, of course, that it is probably higher than the value obtained by Jones & Walker (1988), since this reduction process is unlikely to increase it.

In a highly unbound cluster most of the kinetic energy is associated with expansion, and we expect the kinetic energy of the reduced cluster to be much lower. The virial ratio should then also be lower, and Figure 11 shows that, initially, this is indeed the case. This figure plots not the true virial ratio but the value

$$Q_{\mathrm{obs}} = \frac{R_{\mathrm{h}}\sigma_{\mathrm{obs}}^2}{GM} \tag{13}$$

where σ_{obs} is the three-dimensional velocity dispersion calculated by Jones & Walker (1988):

$$\sigma_{\mathrm{obs}}^2 = \frac{3}{2}\left(\sigma_{\mathrm{rad}}^2 + \sigma_{\mathrm{tan}}^2\right) \tag{14}$$

(with σ_{rad} and σ_{tan} the radial and tangential velocity dispersions respectively after reduction). The initial point is unaffected by reduction since the velocities are generated isotropically, but shortly afterwards the reduction becomes apparent as the velocities become predominantly radial. Thereafter, however, the virial ratio begins to climb as the cluster expands, since σ_{obs} remains roughly constant. The more unbound the model is, the steeper the climb.

Is it possible, therefore, for us to measure a virial ratio of 1.5 (or more) in an expanding cluster? Clearly the answer is yes for highly unbound clusters (e.g. $Q_0 \gtrsim 4$), but we have already seen that such models cannot be scaled to match the ONC in radius without having an unfeasibly young age. In less energetic models, the stars comprising the bound component of the cluster are a complicating factor, but still the majority of stars have predominantly radial velocities in models with $Q_0 \gtrsim 1.5$. For $Q_0 = 2.0$, the reduced virial ratio will eventually climb to 1.5, but in practice by then the cluster has expanded so far that the necessary rescaling once again reduces the cluster age to less than 0.5 Myr. (Recall that t scales as $r^{3/2}$ if we keep G constant.) Only for models with $1.0 \leqslant Q_0 \lesssim 1.5$ do we find cases in which $Q_{\mathrm{obs}} \approx Q$. Here the effect of removing expansion from the data is minimal because the expansion is slow and a significant proportion of the cluster remains bound. Thus we find that Jones and Walker's (1988) value for velocity dispersion is not compatible with a reasonable cluster age for $Q_0 \gtrsim 1.5$.

6 COLD COLLAPSE

We can also consider models starting in an initially cold configuration, with potential energy much greater than their kinetic energy, as might be the case if, for example, the cluster stars formed in a hydrostatically supported cloud. Such a system undergoes an initial collapse, after which it virialises at about half its initial size – subject perhaps to some continuing small oscillation in radius. During the collapse the stars experience a rapidly changing potential as the system heads towards equilibrium – a process known as violent relaxation (Lynden-Bell 1967) – and the point of maximum density is called the *crunch*. In theory this collapse takes roughly a free-fall time of the initial configuration. For a system of mass M and radius R, the free-fall time is

$$T_{\rm ff} = \frac{\pi}{2}\sqrt{\frac{R^3}{2GM}} \tag{15}$$

(see e.g. Binney & Tremaine 1987). The initial density distribution is also important, however, as shown in Figure 12. The collapsing systems shown start with outer radius $R = 4\,\mathrm{pc}$ (ultimately virialising at half that radius), for which the $T_{\rm ff} \approx 3\,\mathrm{Myr}$ for $M = 2000\,\mathrm{M}_\odot$. The collapse from uniform density is clearly closer to the theoretical ideal, and also has a sharper crunch, but the other case shown – an initial distribution going as $1/r^2$– is not much different in terms of collapse time. If we want to model the ONC as a virialised system which has previously undergone cold collapse, we must accept an age of at least 4 Myr.

Alternatively, there is the possibility that the ONC is still in a collapse phase. Aarseth, Lin & Papaloizou (1988) found that in the cold collapse of a system of N members the maximum collapse factor $f_{\rm c} = R_{\rm initial}/R_{\rm crunch}$ at crunch is approximately $N^{\frac{1}{3}}$ (≈ 15 for $N = 4000$). It should be borne in mind that the crunch is only properly defined in systems starting from complete spherical symmetry, uniform density, and no initial kinetic energy. When any of these conditions are broken, the crunch is 'softened' – i.e. more extended in both space and time, and of lower density. The clusters we illustrate here are not strictly cold initially, having $Q_0 \approx 0.1$, so the collapse factor is not as great, typically around 5–10 in the uniform case and as low as 2–3 in systems starting from a $1/r^2$ distribution. (The relaxation is less violent in the latter because they are closer to an equilibrium distribution.)

Figures 13 and 14 show snapshots of the density profile during the collapse in both uniform and $1/r^2$ cases. We are of course free to set the starting radius anywhere between 2 pc and $2f_{\rm c}$ pc, so that the point at which the system matches the ONC in size occurs anytime from $t = 0$ to $t = T_{\rm ff}$ (0 to 20 Myr in the uniform case and 0 to 4 Myr in the $1/r^2$ case, assuming $f_{\rm c} \approx 7.5$ and 2.5 respectively, and using (15)). However as Figure 13 shows, in the uniform case the density profile is not sufficiently centrally condensed until about two thirds of the way through the collapse, corresponding to a minimum age of $\sim 2\,\mathrm{Myr}$. In Figure 13 the choice is somewhat arbitrary, since we are starting from the correct profile. It must be said that none of these collapse profiles could be considered excellent fits to the ONC.

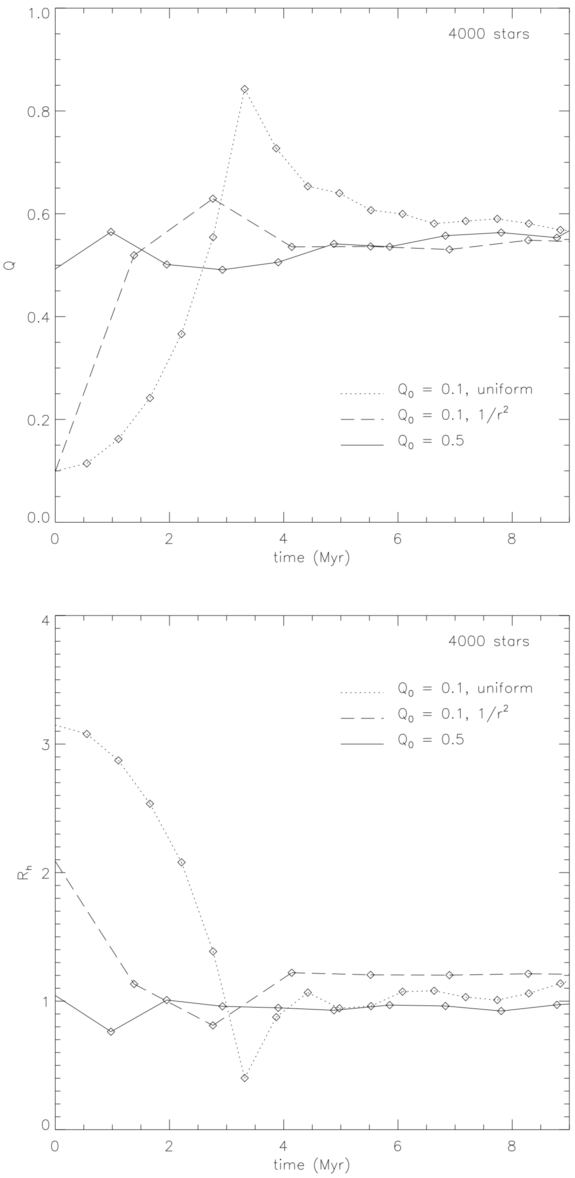

Figure 12. Evolution of Q and $R_{\rm h}$ with time for $Q_0 = 0.1$ (with initially uniform and $1/r^2$ density distributions) and $Q_0 = 0.5$. The initial outer radius of both cold models is 4 pc – note the difference in half mass radius $R_{\rm h}$, and the oscillation after the crunch in the initially uniform case.

7 DISCUSSION

In this paper we have explored a number of different dynamical models for the ONC, and have been able to match many of the observational features discussed in Section 2. We summarise them in Table 1. It is difficult to argue strongly in favour of one particular model, unless we are strict in setting the range of possible ages or are determined to accept the velocity dispersion measured by Jones & Walker (1988). For example if we insist on an age of 1 Myr then the only feasible models are those starting from a $1/r^2$ density distribution with $Q_0 \lesssim 1.5$. Requiring a high velocity dispersion limits us further to models with $1.0 \leqslant Q_0 \lesssim 1.5$.

However, as was noted in Section 2, assigning an age

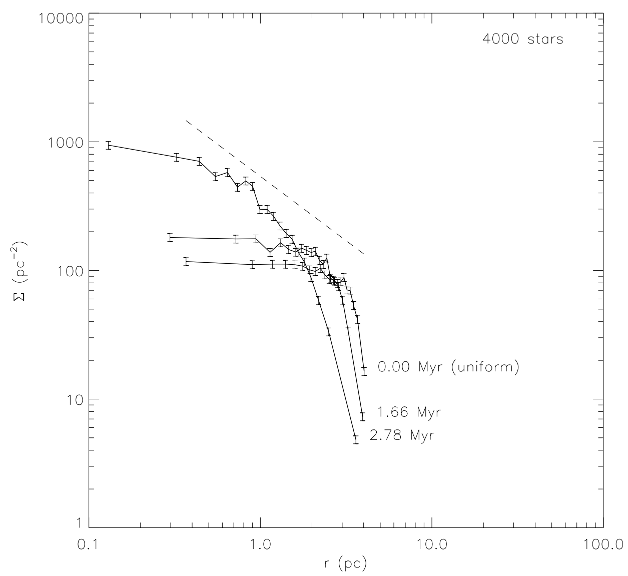

Figure 13. Evolution of the (initially uniform) projected density profile with time for $Q_0 = 0.1$. The dashed line has a slope of -1, corresponding to $1/r^2$ in three dimensions.

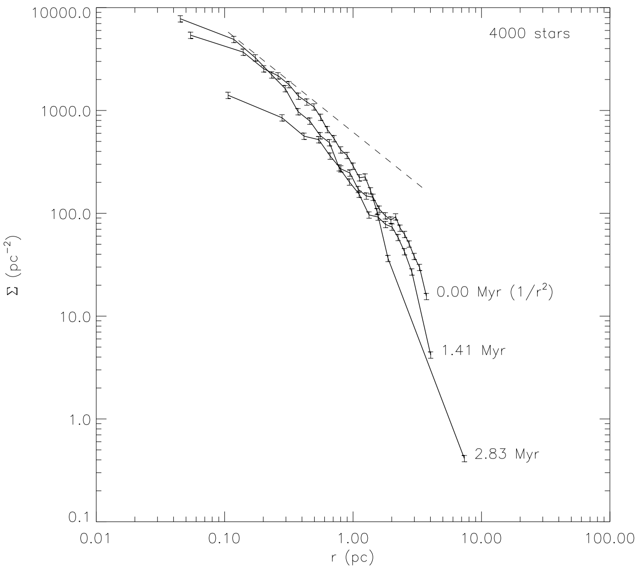

Figure 14. Evolution of the (initially $1/r$) projected density profile with time for $Q_0 = 0.1$. The dashed line has a slope of -1, corresponding to $1/r^2$ in three dimensions.

to the ONC is not so simple. The most recent analysis of the ONC by Palla & Stahler (1999) is in agreement with Hillenbrand's (1997) result that that the great majority of stars there were formed within the past 2 Myr, but with a growing population of 'precursors' starting as long ago as 10 Myr. As they observe, this means the dynamical origins of the cluster are not truly as an N-body system but as a combination of stars and gas. Indeed, they propose that the gradual acceleration of star formation might be the result of an overall contraction in the star forming cloud from which

Table 1. Possible models of the ONC.

Model	Age range (Myr)	Density reduction
Virial equilibrium	$\geqslant 0^a$	1
Unbound: $1 \leqslant Q_0 \lesssim 2$	$\geqslant 0^b$	$\geqslant 1^c$
Unbound: $Q_0 \gtrsim 2$	0–0.5	$\geqslant 1$
Bound remnant of an unbound system	$\geqslant 4$	$1–40^d$
Virial equilibrium after cold collapse	$\geqslant 4$	$8–3000^e$
Collapsing from uniform density	2–20	1
Collapsing from a $1/r^2$ density distribution	0–4	1

For each model we give rough figures for the range of possible ages for which a satisfactory density profile match can be obtained, and the corresponding range in density reduction (previous maximum density / current density). All the models listed match the observational data on the ONC's mass function and population.

[a] Assuming a $1/r^2$ initial density distribution. If it is uniform then the minimum age is about 4 Myr.
[b] Very marginally unbound systems ($Q_0 = 1 + \varepsilon$) can remain close to their original size for a long time.
[c] For $Q_0 = 2.0$, the maximum possible age of ~ 0.5 Myr occurs when the initial half-mass radius is one third its present-day size (see Section 5), corresponding to a 27-fold reduction in density, but we can make the initial cluster smaller still if we ignore the age constraint.
[d] Only one fifth of the stars in a cluster with $Q_0 = 2$ remain, so the initial density is 40 times greater than that of the remnant if the latter doubles in radius (see Section 5).
[e] Maximum density occurs at the crunch: 8 times greater than the subsequent (virialised) state in the case of a $1/r^2$ cluster with collapse factor $f_c = 2$, 3000 times greater for a uniform cluster with $f_c = 15$.

the ONC was born. We cannot accurately model this with a code such as NBODY6 nor account for the effect of the changing number of stars and diminishing gas fraction, without considerable modification (or even a different code, for example using smoothed particle hydrodynamics). In general, as an N-body system the ONC is difficult to investigate because it is close to its initial state, and close to initial conditions which were determined by processes other than stellar dynamics.

There are also some observational features of the ONC and its environment which we have not included in our models, but which may have had an influence on the ONC's dynamics. For example, the shape of the cluster, discussed in Hillenbrand & Hartmann (1998), is not in fact spherical, having an aspect ratio of 2:1 at the 2 pc radius. Larger scale surveys (Parsamian & Chavira 1982; Nakano, Wiramihardja & Kogure 1995) show it to be part of a larger linear distribution of stars. This suggests that its origins may not have been spherically symmetric either, which would be most relevant to the cold collapse models discussed in Section 6. We have also ignored the possibility of stellar evolution in the cluster – probably a reasonable simplification for such a young system, but on a longer timescale the evolution of the most massive stars may well be important. Also, we have considered the cluster in isolation, neglecting the presence of the surrounding molecular cloud, which may contribute a background or tidal gravitational potential.

Nevertheless, despite the caveats associated with each of the models listed in Table 1, and the fact that the data do not unambiguously point towards any particular one, we are confident that even if they do not constitute the whole picture, they represent an important part of it. If stellar dynamics and the processes described in this paper have not necessarily been the dominating influences in the cluster's evolution up to now, they will certainly dominate its future.

7.1 Fate of the ONC

The timescale over which the stars in the ONC will disperse into the Galactic field may be only a few million years if the cluster is unbound. If it is bound, the evaporation time can be can be estimated as

$$T_{\rm e} \approx \frac{10N}{\ln N} T_{\rm c} \tag{16}$$

(Binney & Tremaine 1987), which comes to several billion years for $N \approx 4000$. Even in marginally unbound cases, we saw in Section 5 that a significant fraction of stars can remain bound, in which case the medium-term future of the ONC will be as an open cluster, such as the Pleiades, which contains 2–3 thousand stars with a mean age of about 100 Myr. Kroupa et al. (2001) have demonstrated that with a star formation efficiency of ~ 0.3 their models of the ONC evolve to a system similar to the Pleiades, and our survey of possible dynamical models here has shown this model (corresponding to $Q \approx 1.5$) to be perhaps the one most consistent with observational constraints.

7.2 Birthplace of the Solar system

In the introduction we discussed evidence suggesting that most stars in the Galaxy, our own included, formed in an environment like the ONC. There are other indicators which we did not mention. For example, the Solar system may itself bear some imprint of its natal environment, in the composition of meteorites bombarding Earth today. These suggest an unexpectedly high abundance of certain short-lived radioactive isotopes in the very early Solar system (see e.g. Goswani & Vanhala 2000). One obvious cause for this might have been the presence of a nearby massive star, enriching the early Solar nebula via a supernova explosion, and we have seen that such stars are most commonly found in populous environments like the ONC. Adams & Laughlin (2001) have considered this possibility in combination with the requirement that the young Solar system remains undisrupted (which makes very populous early environments less likely). In their dynamical simulations any significant perturbation of the eccentricities or orbital inclinations of planets in the early Solar system was considered sufficient to lead to disruption. Their argument thus assumes that the Sun remained in its early dense environment long enough for a planetary system to have formed – which may have taken several million years (e.g. Lissauer 1993; Pollack et al. 1996). They concluded that the most likely birth environment for the Sun under this hypothesis was one containing 1000–3000 other stars.[**]

Similarly, Gaidos (1995) has analysed the effect of stellar encounters on the orbits of Uranus and Neptune if the Solar system spent a time T in an environment of density n. He concluded that their current orbital inclinations (0.77 and 1.77 degrees respectively) set an upper limit of $3 \times 10^4\,{\rm M_\odot\,pc^{-3}\,Myr}$ on the product nT. If the ONC is bound, this is incompatible with the Solar system having spent more than a few million years in a cluster like it. If it is unbound, however, its density will drop, perhaps leaving behind an open cluster with a density of $\sim 10^2\,{\rm stars\,pc^{-3}}$. The Solar system could plausibly have remained in such an environment for several hundred million years.

8 CONCLUSIONS

8.1 Permitted models for the ONC

The density profile of the ONC is best fit by dynamical models in which the cluster is initially in virial equilibrium, with a $1/r^2$ density profile and a stellar distribution that extends well beyond the region of current surveys. If we were prepared to ignore the evidence that the ONC is somewhat unbound, we would then settle for this (arguably dull) conclusion that the ONC formed in a state close to its current one.

However, if we take seriously the evidence that the ONC is unbound and/or we are prepared to accept models with a somewhat inferior fit to the density profile (i.e. models that are generally a bit too steep in the outer regions), we would favour/accept a range of other models.

The claim that the ONC is currently unbound leads us to explore models in which it became unbound at some stage in its former history. If the cluster was 'born' in an unbound state, and if we are prepared to accept that the ONC is not much younger than 2 Myr, then we are only allowed models in which the ONC has expanded quasi-statically (i.e. with expansion velocity much less than its velocity dispersion). Such quasistatic expansion can result either from gradual gas loss or, as in the simulations explored here, from the initial virial ratio (being in the range $1 - 1.5$) implying marginally unbound conditions. In either case, the result of quasi-static expansion is a bound core and an unbound halo of stars leaving the cluster. On the other hand, if the cluster became unbound at arbitrarily recent times, then it could be currently undergoing rapid expansion, which would have been factored out of the Jones and Walker proper motion experiment.

If we again neglect the evidence that the ONC is currently unbound, we can also entertain cold collapse models. If we accept an age of 2 Myr for the ONC, then the present cluster would still be in the collapse phase (i.e. not yet reached the maximum density 'crunch'). If the cluster is older than ~ 4 Myr, then it could already have passed

[**] There is an alternative hypothesis: that the abundance of radioactive nuclei was caused by some process of self-enrichment in the Solar nebula (e.g. Lee et al. 1998), and therefore tells us nothing about the Sun's early environment.

through the crunch in the past, and be currently in a state of virial equilibrium.

8.2 Implications of these models for the maximum density of the ONC in the past

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One of the chief motivations for this study was to discover if the ONC could have originated from conditions that were much denser than its current state. In the quasi-static expansion models described in 8.1 above, the density of the cluster may drop by $1-2$ orders of magnitude due to a mixture of expansion and loss of stars from the system. In the rapid expansion models (where the putative gas loss must have occurred very recently), the cluster could have in principle expanded from arbitrarily dense initial conditions. In cold collapse models, the cluster was of course less dense in the past if it is still in the collapse phase. However, if it has gone through the crunch and rebounded it may have been up to $3-4$ orders of magnitude denser at the crunch than it is now, although this phase of maximum compression would have been short ($\sim 10^5$ years).

8.3 Future observational discriminants

Further progress requires a better knowledge of the cluster kinematics. In particular, it is crucial to measure stellar velocities by a method that does not subtract out any mean cluster expansion or contraction. If one believes one knows the cluster mass accurately, then the accurate measurement of the rms velocity in such an experiment would yield the value of the virial ratio and hence settle the issue of boundedness. However, uncertainties in the cluster mass imply that a more robust result may be obtained by considering instead the *isotropy* or otherwise of the stellar motions. For example, the recent rapid expansion model would be unambiguously detectable as a mean outward radial streaming motion. The quasi-static expansion model would also leave signatures in terms of a bound core (with largely isotropic) velocities and an unbound (outwardly streaming halo). Likewise, any net inward streaming motion (as in cold collapse models prior to the crunch) would be detectable.

9 ACKNOWLEDGEMENTS

We thank Matthew Bate, Sverre Aarseth, Ian Bonnell, Lynne Hillenbrand, Burt Jones, Donald Lynden-Bell, and Mark McCaughrean for valuable help and discussions. A. Scally is grateful for funding from the European Commission Research Training Network HPRN-CT-2000-00155: The Formation and Evolution of Young Stellar Clusters.

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