On the Binary Properties and the Spatial and Kinematical Distribution of Young Stars

Pavel Kroupa
Institut f"ur Theoretische Astrophysik, Universit"at Heidelberg,
Tiergartenstr. 15, D-69121 Heidelberg, Germany
e-mail: pavel@ita.uni-heidelberg.de

Summary

The effects which star cluster concentration and binarity have on observable parameters, that characterise the dynamical state of a population of stars after their birth aggregate dissolves, are investigated. To this end, the correlations between ejection velocity, binary proportion, mean system mass, binary orbital period and mass ratio are quantified for simulated aggregates. These consist of a few hundred low-mass binary and single stars, and have half-mass radii in the range 2.5 to 0.08 pc. The primordial binary-star population has a period distribution similar to that observed in Taurus-Auriga for pre-main sequence binaries. The findings presented here are useful for interpreting correlations between relative locations and proper motions, binary properties and masses of young stellar systems within and surrounding star forming regions, and of stellar systems escaping from Galactic clusters.

For the low-concentration binary-rich aggregates, the proportion of binaries decreases monotonically as a function of increasing ejection velocity after aggregate dissolution, as expected. However, this is not the case for initially highly concentrated binary-rich aggregates. The reason for this difference is the interplay between the disruption of binary systems and the initial depth of the potential well from which the stellar systems escape.

After aggregate dissolution, a slowly expanding remnant population remains. It can have a high binary proportion (80 per cent) with a high mean system mass, or a low binary proportion (less than about 20 per cent) with a low mean system mass, if it was born in a low- or a high-concentration aggregate, respectively. It follows that adjacent regions on the sky near some star-forming clouds can have young populations with different binary proportions and different mass functions, even if the binary proportion at birth and the initial mass function (IMF) were the same.

Binary systems that are ejected from the aggregate tend to be massive, and their mass ratio tends to be biased towards higher values. The mean system mass is approximately independent of ejection velocity between 2 and 30 km/s. Dynamical ejection from binary-rich aggregates adds, within 10 Myr, relatively massive systems to regions as far as 300 pc from active star-forming centres. Long-period systems cannot survive accelerations to high velocities. The present experiments show that a long-period (> $10^4$ d) binary system with a large velocity (> 30 km/s) cannot be ejected from an aggregate. If such young systems exist, then they will have been born in high-velocity clouds.

Subject headings: stars: formation – stars: pre-main-sequence – stars: low-mass, brown dwarfs – stars: kinematics – stars: statistics – binaries: general
1. Introduction

Stellar systems (i.e. single or multiple stars) form in groups. The dynamical processes within these alter the properties of the young systems when they leave the site where they formed. The dynamical properties of a stellar system are its mass (i.e. luminosity if age is known), the multiplicity and the orbital parameters if it is a multiple system. The distribution of velocities of young stars emanating from star-forming centres (i.e. the kinematical signature of star formation) will also be affected by the dynamical interactions within the young groups. Both, the distribution of dynamical properties and the kinematical signature of star formation bear an imprint of the dynamical configuration at the time when the stellar group was born.

Star formation in Taurus-Auriga gave birth to aggregates with sizes of roughly 0.5–1 pc consisting of about 20–50 stars. It is now well established that most stars form in binary systems in Taurus-Auriga (e.g. Köhler & Leinert 1998). The same appears to hold true in other star-forming regions (Ghez et al. 1997). Embedded clusters may also have a binary proportion that is higher than in the Galactic field (Padgett, Strom & Ghez 1997). In the Trapezium cluster, which is a very dense embedded cluster and probably less than 1 Myr old, Prosser et al. (1994) find a binary proportion that is at least as large as in the Galactic field. In the cluster core, Petr et al. (1998) observe, for low-mass stars, a binary proportion similar to the Galactic field, and smaller by about a factor of three than the binary proportion in Taurus-Auriga. These findings are particularly interesting, because binary destruction is expected to be efficient in such an environment. A review of pre-main sequence binary stars, and their relation to Galactic field systems, is provided by Mathieu (1994, see also Kroupa 1995a, Simon et al. 1995). Young Galactic clusters also contain binary systems. The particularly well studied Pleiades and Praesepe clusters have binary proportions of 40–50 per cent, for systems of spectral type earlier than K0 (Raboud & Mermilliod 1998a, 1998b).

There exists thus evidence that the formation of binary systems may be by far the dominant star-formation mode in both loose groups and highly concentrated embedded clusters, some of which may evolve to bound Galactic clusters. The term aggregates is used henceforth to mean loose groups or embedded clusters of more than 10 stars.

If stars form predominantly in aggregates of binary systems, then the kinetic energy distribution after aggregate dissolution should be enhanced at high energies, when compared to dissolved aggregates of single stars, because binary star binding energy can transform into kinetic energy (Heggie 1975, Hills 1975, Hut 1983). Large accelerations are destructive to binary systems, so that the proportion of binaries should be a decreasing function of increasing final kinetic energy. Additionally, different initial aggregate concentrations lead to different final binary proportions and kinematical signatures, as will be shown here. This is also true under the extreme assumption that all stars always form in binary systems with the same initial dynamical properties. This dynamical mechanism of producing variations in binary proportion and associated dynamical properties stands in contrast to a possible variation of these parameters determined by the star-formation process. Durisen & Sterzik (1994) make the interesting point that the binary proportion may be smaller in molecular clouds with a higher temperature than in lower-temperature clouds.

It is important to study the signatures that arise from purely dynamical interactions in stellar groups, for a comparison with outcomes from usually less well-understood alternative scenarios. In a study of the large-scale distribution of young stars around active star-forming regions, Sterzik & Durisen (1995) find that the dynamical decay of small stellar groups can lead to sufficiently large velocities to populate large areas on the sky with young stars, so that these need not have formed near their observed location. They find that special initial dynamical configurations of the stars (e.g. cold thin strings) lead to enhanced production of ejected stars. Initial decay of cold sub-groups within larger complexes also has this effect.
(Aarseth & Hills 1972), and scattering of proto-stars on cloud clumps during an even earlier dynamical phase may likewise eject very young low-mass stars (Gorti & Bhatt 1996). However, the number of ejected stars cannot account for the observed number of widely distributed young stars (Feigelson 1996). The evolution of circum-stellar discs around stars ejected from small stellar groups is studied by Armitage & Clarke (1997), and McDonald & Clarke (1995) show that the presence of circum-stellar material in small proto-stellar groups increases the number of binaries formed and randomises the mass-ratio distribution. That the number of dynamically ejected stars is increased significantly in binary-rich stellar aggregates, when compared to clusters consisting initially only of single stars, is shown by Kroupa (1995c). These simulations show that a mass-ratio distribution produced by randomly associating masses from the IMF, decays to the observed distribution for G-dwarf binaries, if most stars form in aggregates similar to observed embedded clusters. Also, initially more concentrated aggregates produce more stars with a high ejection velocity, the maximum of which increases with decreasing cluster radius. De la Fuente Marcos (1997) investigates the dependence on cluster richness, and finds that the mean ejection velocity increases for more initially populous clusters. Ejection velocities larger than a few hundred km/s can be achieved in young star clusters containing massive primordial binaries (Leonard & Duncan 1990). This may explain the location of OB stars far from active star-forming sites. Leonard (1991) finds, on the basis of many scattering experiments, that the maximum ejection velocity is of the order of the escape velocity from the stellar surface of the most massive star. If its mass is 60 $\text{M}_\odot$, then a similar star can attain an ejection velocity of up to 700 km/s. A low-mass star may find itself fleeing with a velocity of up to 1400 km/s, after a surface-grazing encounter with such a star. A critical discussion of the possible origin of runaway OB stars is provided by Leonard (1995). He stresses that collisions of two stars during binary-binary interactions can produce runaway OB stars with very similar properties as in the alternative scenario, in which such stars result from a supernova explosion in close binary systems. An interesting and insightful discussion of the implications of the binary properties of runaway OB stars for the dynamical configuration of massive stars at birth is to be found in Clarke & Pringle (1992).

In this paper, the correlations between stellar velocity, system mass and binary proportion that arise from aggregates with different initial concentration and consisting initially either of 400 single stars or of 200 binary systems, is studied. The resulting correlations are useful for interpreting the properties and distribution of young stars near and in star forming regions (see for example Brandner et al. 1996, Feigelson 1996, Frink et al. 1997).

In Section 2.1 the assumptions, simulations and definitions are described. The results are presented in Section 3, and Section 4 contains the conclusions.

2. Method

The initial conditions and numerical method are described in Section 2.1, and the data analysis is outlined in Section 2.2.

2.1. Assumptions

$N_{\text{bin}} = 200$ binary systems are distributed in virial equilibrium according to the Plummer density law, with initial half mass radii $R_{0.5} = 2.53, 0.77, 0.25, 0.077$ pc. These approximately span the region of parameter space similar to distributed (e.g. Taurus-Auriga) and very tightly clustered (e.g. Trapezium cluster)
star formation. The clusters have zero initial centre-of-mass velocities in the local standard of rest. The $R_{0.5} = 0.8$ pc aggregate is especially interesting, because inverse dynamical population synthesis (Kroupa 1995a,b) suggests that it may be representative of the dynamical structures in which most stars form (compare with Lada & Lada 1991).

While the mechanism of binary system formation cannot be specified in detail, the assumption that the majority of all stars form in binaries is supported by observational evidence (see review by Mathieu 1994), and by recent advances in the theory of star formation (for reviews see Boss 1995, Clarke 1996). However, theory cannot, at present, constrain the early dynamical properties of stellar systems. The interesting suggestion has been made (Durisen & Sterzik 1994) that cloud temperature may influence the binary proportion, such that it may be lower in dense embedded clusters. For comparison with the binary rich aggregates, $N_{\text{sing}} = 400$ single stars are distributed in aggregates, initially with $R_{0.5} = 0.25, 0.077$ pc.

The initial velocity dispersion, $\sigma$, and escape velocity from the centre of the aggregates, $v_{\text{esc}} = \sqrt{2\phi} (\phi$ is the Plummer potential at the origin), are: $\sigma = 0.3$ km/s, $v_{\text{esc}} = 0.77$ km/s ($R_{0.5} = 2.5$ pc), $\sigma = 0.5$ km/s, $v_{\text{esc}} = 1.4$ km/s ($R_{0.5} = 0.8$ pc), $\sigma = 0.9$ km/s, $v_{\text{esc}} = 2.4$ km/s ($R_{0.5} = 0.25$ pc), and $\sigma = 1.7$ km/s, $v_{\text{esc}} = 4.4$ km/s ($R_{0.5} = 0.08$ pc). Other physical parameters are listed in table 1 of Kroupa (1995a). Aarseth’s NBODY5 programme (Aarseth 1994) is employed for the N-body simulation of the dynamical evolution of each aggregate in a standard Galactic tidal field.

In order to simplify the computational burden, the stars are treated as point particles and stellar evolution is neglected. The assumption of virial equilibrium is the simplest case, and implies that the results presented here are strictly only applicable to escaping stars from Galactic clusters. The present results can, however, also be used as guidelines of the type of correlations one might find after embedded clusters dissolve. An explicit formulation of this problem requires treatment of gas expulsion, and thus the introduction of additional ill-defined parameters. As gas expulsion is not treated here, the results are representative of star formation with high efficiency, i.e. aggregates with low residual gas content. In the alternative case of a low star formation efficiency, the major effect gas expulsion has, is a shortening of the time-scale during which the dynamical evolution occurs. This can be compensated for by a reduction of $R_{0.5}$, in order to obtain the same effective dynamics (section 6.4 in Kroupa 1995a). The initial $v_{\text{esc}}$ is then larger.

Stellar masses, $m$, with $0.1 \, M_\odot \leq m \leq 1.1 \, M_\odot$, are obtained from the IMF: $\xi(m) \propto m^{-\alpha_1}$, $\alpha_1 = 1.3$ for $0.08 \, M_\odot \leq m < 0.5 \, M_\odot$, $\alpha_2 = 2.2$ for $0.5 \, M_\odot \leq m < 1.0 \, M_\odot$ (Kroupa, Tout & Gilmore 1993), and $\alpha_3 = 2.7$ for $1.0 \, M_\odot \leq m$ (Scalo 1986), where $\xi(m) \, dm$ is the number of stars with masses in the range $m$ to $m + dm$. The mean stellar mass is $0.32 \, M_\odot$, and the mass of each aggregate amounts to $M_{\text{tot}} = 128 \, M_\odot$. Adopting for the mass of B stars $6 - 18 \, M_\odot$, each should have associated with it 280 stars with mass in the range $0.08 - 1 \, M_\odot$. The maximum ejection velocity that can be achieved is thus limited to about 600 km/s for $0.1 \, M_\odot$ stars, and about 300 km/s for G-dwarfs (Leonard 1991).

The main-sequence mass-ratio distribution for G-dwarf binaries (Duquennoy & Mayor 1991) is not consistent with random pairing from the IMF, but may be derived from this assumption if most stars form in embedded clusters (Kroupa 1995a,b). In accordance with this result, and the evidence presented by Leinert et al. (1993), stellar masses are combined at random to generate the initial binary-star population. Special care must be taken when interpreting an observed mass-ratio distribution, as it can be affected significantly by even simple observational bias (Trimble 1990, Tout 1991).

Binary systems must arrive on the birth-line with eccentricities approximately dynamically relaxed, because subsequent thermalisation in the stellar aggregate is not efficient enough to produce such a
distribution (Kroupa 1995b). This is because the cross-section for a significant change in eccentricity decreases very steeply with increasing distance of closest approach of a perturber (Heggie & Rasio 1996). Consequently, the initial eccentricity distribution is taken to be dynamically relaxed. The results are not sensitive to this assumption, however.

An initial period distribution that is consistent with the observational data for young binaries is used. The orbital periods, $P$ (in days), form a flat distribution, $f_P(\log_{10}P) = [\log_{10}(P_{\text{max}}) - \log_{10}(P_{\text{min}})]^{-1}$ (equation 3 in Kroupa 1995a), with $\log_{10}P_{\text{min}} = 3$, $\log_{10}P_{\text{max}} = 7.5$ and $P_{\text{min}} \leq P \leq P_{\text{max}}$.

For each binary and single-star aggregate, $N_{\text{run}} = 5$ and 3 simulations, respectively, are carried through.

2.2. The observables

All results quoted here are averages of $N_{\text{run}}$ simulations that are evaluated after 1 Gyr, i.e. after the aggregates have dissolved. Aggregate dissolution occurs after $700 \pm 130$ Myr in all cases, when the number of stars in a volume with a radius of 2 pc, that is centred on the density maximum of the cluster, has decayed to 3 of less.

The velocity-dependent binary proportion is

$$f_v = \frac{N_{\text{bin},v}}{(N_{\text{sing},v} + N_{\text{bin},v})},$$

(1)

where $N_{\text{sing},v}$ and $N_{\text{bin},v}$ are the number of single-star and binary systems, respectively, in a velocity interval $v$ to $v + \Delta v$ relative to the local standard of rest. The binary proportion in some sub-domain, which may, for example, be the period range or spatial region accessible to the observer, is $f = N_{\text{bin}}/(N_{\text{sing}} + N_{\text{bin}})$, where $N_{\text{sing}}$ and $N_{\text{bin}}$ are the number of single and binary systems, respectively, in the sub-domain. Similarly, $f_{\text{tot}}$ is the binary proportion of the entire population.

The mean system mass in the velocity interval is

$$<m>_v = \frac{M_v}{(N_{\text{sing},v} + N_{\text{bin},v})},$$

(2)

where $M_v$ is the total stellar mass in the velocity interval. Initially, i.e. at $t = 0$, $f_v = 1$ and $<m>_v = 0.64 M_\odot$ independent of $v$ for the binary-star aggregates, and $f_v = 0$ with $<m>_v = 0.32 M_\odot$ for the single-star aggregates.

The relative proportion of systems in a velocity interval is

$$h_v = \frac{(N_{\text{sing},v} + N_{\text{bin},v})}{(N_{\text{sing},\text{tot}} + N_{\text{bin},\text{tot}})}.$$  

(3)

Note that this is $f_v$ in Kroupa (1995c).

The circular orbital velocity, $v_{\text{orb}}$ [km/s], of a binary star with system mass, $m_{\text{sys}}$ [$M_\odot$], and orbital period, $P$ [days], is
\[ \log_{10} P = 6.986 + \log_{10} m_{\text{sys}} - 3 \log_{10} v_{\text{orb}}. \] (4)

The primordial binary population used here has a maximum \( v_{\text{orb}} = 27.7 \) km/s (for \( P = 10^3 \) d, \( m_{\text{sys}} = 2.2 \, M_{\odot} \)) and a minimum \( v_{\text{orb}} = 0.39 \) km/s (\( P = 10^7.5 \) d, \( m_{\text{sys}} = 0.2 \, M_{\odot} \)).

Finally, a stellar system that is ejected has a final (i.e., evaluated after 1 Gyr) velocity \( v \geq 2 \) km/s.

3. Results

Long distance encounters between systems (two-body relaxation) and in addition scattering of systems on the non-uniform background potential (collective effects) dominates the dynamical evolution of the aggregates. Relatively energetic, stochastically occurring encounters between stellar systems can lead to the ionization of binary stars and to the acceleration of a system to escape velocity from the aggregate.

If the mean kinetic energy of the population is \( \bar{E}_{\text{kin}} \) and the binding energy of a binary is \( -E_{\text{bin}} = -G m_1 m_2/(2a) \), where \( m_1 \) and \( a \) are the masses of the components and the semi-major axis, respectively, then a binary is termed hard if \( E_{\text{bin}}/\bar{E}_{\text{kin}} > 1 \). Hard binaries are likely to gain binding energy, i.e., to harden (Heggie 1975, Hills 1975), in which case the perturber can be accelerated to escape velocity. The resulting hardened binary suffers a recoil which may be sufficient to also expel it from the aggregate.

These processes change the distributions with velocity of the number of systems, \( h_v \), of the binary star proportion, \( f_v \), of the mean system mass, \( \langle m \rangle_v \). Also, the correlations between binary-star binding energy, \( E_{\text{bin}} \), and kinetic energy, \( E_{\text{kin}} \), and between the velocity, \( v \), and orbital period, system mass and mass ratio, evolve. The distributions that emerge after aggregate dissolution thus contain information about the initial dynamical configuration, but care must be taken in interpreting distribution data. This is the subject of the present section.

3.1. Distribution of velocities

In Fig. 1, \( h_v, f_v \) and \( \langle m \rangle_v \) are plotted as a function of velocity for the binary star aggregates with \( R_{0.5} = 2.5, 0.8, 0.25, 0.08 \) pc. Fig. 2 contains the same information for the two single star aggregates. In Table 1, column 1 contains the centre of each logarithmic velocity bin. Columns 2–7 list, for each aggregate, the fraction, \( h_v \), of systems per logarithmic velocity bin.

After aggregate dissolution, most systems have a velocity near 0.35 km/s (Figs. 1 and 2). A slight shift in the maximum of \( h_v \) towards smaller \( v \) with decreasing \( R_{0.5} \) comes about, because systems have to overcome the initial aggregate potential before escaping. The cooling is much more pronounced in the absence of binary star heating (Fig. 2), and during the first few cluster crossing times. Later, the aggregate expands to fill its tidal radius and loses memory of its initial concentration. Initially very concentrated aggregates, and those with large \( R_{0.5} \), have an indistinguishable life-time (Kroupa 1995c). The binary star population, however, retains this memory (Kroupa 1995a).

For aggregates with initially smaller \( R_{0.5} \), an increase in the proportion of systems with \( v > 2 \) km/s results. Comparison of Figs. 1 and 2 shows that, for the same \( R_{0.5} \), aggregates initially with a high proportion of binary systems have significantly larger \( h_v \) at \( v > 2 \) km/s, than aggregates that consist
initially only of single stars. A high proportion of primordial binary systems thus increases the percentage of ejected systems.

3.2. Binary proportion

High velocity systems are expected to be primarily single stars, because only relatively hard binaries can survive the large accelerations during the encounter, as is also stressed by Sterzik & Durisen (1995). This is borne out for the $R_{0.5} = 2.5, 0.8, 0.25$ pc aggregates (Fig. [3]), and also in the simulations reported by Leonard & Duncan (1990, their figs. 4 and 5) and also fig. 9 in Kroupa (1995c).

Dynamical evolution is quiescent in star forming regions where the stellar systems freeze out of the gas in low-density aggregates. The $R_{0.5} = 2.5$ pc aggregate approximates this situation. In this aggregate, a binary with $m_{\text{sys}} = 0.2 M_\odot$ and $P = 10^{7.5}$ d has $v_{\text{orb}} = 0.39$ km/s, which is comparable to the velocity dispersion. The entire binary population is therefore hard, and indeed most binaries survive cluster evolution. From such aggregates results a high ($f_v > 0.8$) proportion of binaries for systems with approximately $v < 1$ km/s. Only 2.6 per cent of the systems end up with $v > 5$ km/s (Table [3]), and these have a binary proportion of approximately $f_v < 0.1$ (Fig. [3]).

For the $R_{0.5} = 0.8$ pc aggregate, a relatively high proportion of binaries ($f_v > 0.8$) among systems that have $v < 0.3$ km/s is obtained. Significant differences between the binary proportions in the two models can be found in the velocity intervals a) $-0.5 < \log_{10} v < 0$ and b) $0.1 < \log_{10} v < 0.6$. In interval (a), $f_v \approx 0.9, 0.6$ and in interval (b), $f_v \approx 0.05, 0.15$, for $R_{0.5} = 2.5, 0.8$ pc, respectively. Of all systems that finally emerge from such an aggregate, 4 per cent have a velocity $v > 5$ km/s. These have a slightly larger binary proportion than for the $R_{0.5} = 2.5$ pc case discussed above. Overall, for $R_{0.5} \geq 0.8$ pc, $f_v$ decreases monotonically with increasing $v$, and escaping stars have a low ($f_v < 0.2$) binary proportion.

Star formation in denser aggregates ($R_{0.5} < 0.8$ pc) leads to significantly different behaviour of $f_v$ with $v$ (Fig. [3]). For $R_{0.5} = 0.25$ pc, $f_v \approx 0.45$ for $v < 1$ km/s, with a discontinuous decrease to $f_v \leq 0.2$ for $v > 1$ km/s.

Of special interest is the $R_{0.5} = 0.08$ pc model. It represents most closely the Trapezium cluster, because it has a comparable central number density, half-mass radius and velocity dispersion. In the present model, the initial crossing and relaxation times are $t_{\text{cr}} = 1 \times 10^5$ yr and $t_{\text{rel}} = 3 \times 10^5$ yr, respectively (Table 1 in Kroupa 1995a), whereas in the Trapezium cluster, $t_{\text{cr}} \approx 4 - 12 \times 10^5$ yr and $t_{\text{rel}} \approx 0.7 - 3.7$ Myr (Bonnell & Kroupa 1998). The Trapezium cluster, however, is different in that it contains 500–1000 stars with a mean mass of about 0.6 $M_\odot$, and in that it is the core of the much more massive and extended Orion Nebula Cluster (Hillenbrand & Hartmann 1998). Also, it is not clear if the entire cluster is gravitationally bound.

After dissolution of this $R_{0.5} = 0.08$ pc aggregate most systems have $v < 1$ km/s (Fig. [3]). The proportion of binary stars shows a rather complex dependence on $v$. The binary proportion ranges from $f_v \approx 0.1$ for systems with $v \approx 0.1 - 0.2$ km/s to $f_v \approx 0.6$ for $v \approx 1$ km/s; $f_v$ thus increases with $v$ for $v < 1$ km/s. The binary proportion shows a significant maximum ($f_v \approx 0.6$) near $v \approx 1$ km/s, and remains approximately constant at $f_v \approx 0.25$ for $3$ km/s $< v < 20$ km/s. In this rather extreme model of star formation, 4.6 per cent of all systems have $v > 5$ km/s after aggregate dissolution. The low value of $f_v$ for small $v$, and its rise with $v$, is due to efficient disruption of binaries at an early dynamical age, when the ejected stars are decelerated most effectively by the young deep potential well. A fraction of
the predominantly single stars with low velocity, is also a decelerated part of the high-velocity tail in the aggregates with $R \geq 0.8$ pc. This can be inferred from Figs. 3 and 4 (Section 3.4). Hardened binaries ($\log_{10} P < 4$) are found with small velocities. Usually they are the result of energetic three-body or binary-binary interactions causing ejection.

Thus, in a realistic embedded cluster with the same stellar mass, the initial escape velocity is larger because the potential is dominated by the gas. Within a few Myr most of the gas is expelled, leaving an expanding cluster population, and a binary deficient remnant population, in which each system has a small centre-of-mass velocity. This decelerated and binary deficient population remains bound to the molecular cloud and, after a few Myr, contributes to a distributed population of young stars with significantly different dynamical properties to the distributed population in Taurus-Auriga. Dispersal of this binary deficient population takes long, and an observer finds a loosely distributed group of stars of similar age, and with a reduced binary proportion that depends on the initial cluster concentration.

Concerning the aggregates with initially no primordial binaries (Fig. 2), more binaries form by capture in the initially more concentrated aggregate ($R_{0.5} = 0.08$ pc), owing to the more frequent three-body encounters in the young concentrated aggregate. The resulting total binary proportion, however, remains insignificant (Kroupa 1995a). The data plotted in Fig. 3 indicate that $f_v$ increases with $v$ (for $v > 1$ km/s), which is contrary behaviour to the aggregates that contain a large population of primordial binaries.

### 3.3. Mean system mass

In a binary-binary or binary-single star encounter, binding energy can be transformed into kinetic energy of the escaping stellar system. A given acquired kinetic energy corresponds to a smaller ejection velocity if the system mass is larger. Low-mass stars can be ejected with higher velocities than high-mass stars. The extensive simulations performed by Leonard & Duncan (1990) and Leonard (1991, 1995) demonstrate that this is the case, and are consistent with the observational mass-velocity diagram for OB stars produced by Gies & Bolton (1986). This is also discussed in length by Conlon et al. (1990).

The present study concentrates on the mean-system-mass–velocity relationship obtained from self-consistent $N$-body simulations of clusters of low-mass stars ($m \leq 1.1 M_\odot$), and is thus relevant for the large-scale distribution of young-low mass stars seen in the ROSAT survey (compare with Sterzik & Durisen 1995).

As is evident from Figs. 1 and 2, the behaviour of $< \langle m \rangle_v$ with $v$ is complex and depends on the initial concentration of the aggregate. The complexities of the underlying binary–binary and triple-star encounters are discussed at length by Harrington (1975), Heggie (1975), Hills (1975), Leonard & Duncan (1990) and Leonard (1991, 1995), and a review can be found in Valtonen & Mikkola (1991). The most-apparent result here is that the expected simple correlation (smaller $< m \rangle_v$ for larger $v$) does not hold, except for the $R_{0.5} = 2.5$ pc aggregate. The few stars that are ejected from this aggregate are low-mass stars expelled from unstable triple or higher-order systems (Heggie 1975, Harrington 1975, Hills 1977, compare also with the second-mass-family interactions of Leonard 1991, and with Kiseleva, Eggleton & Orlov 1994).

The expected correlation is also observed for $v > 30$ km/s for all binary-star aggregates. An acceleration beyond this velocity, which is the orbital velocity of the hardest primordial binary in the present simulations (Section 2.2), is destructive to all primordial binaries. Only single stars appear with such large velocities.

For $R_{0.5} = 0.8, 0.25$ and $0.08$ pc, the velocity range $v \approx 2$ km/s to $30$ km/s yields no clear correlation
between $<m>_v$ and $v$: $<m>_v \approx 0.5 M_\odot$ is approximately constant. This is an interesting finding which was also noted by Harrington (1975). It shows that systems more massive than $0.5 M_\odot$ are ejected from aggregates similar to embedded clusters, with velocities that can place them at distances between 20 and 300 pc within 10 Myr of ejection time from their formation site. These systems result from stochastic and quite energetic binary-binary and three-body encounters.

The majority of systems that have $v < 1$ km/s, and which do not spread much further than 1–10 pc from their formation site within 10 Myr, have a constant $<m>_v$ that lies between the average stellar mass and mean primordial system mass. Smaller values are seen for binary-poor remnant populations (e.g. for $R_{0.5} = 0.08$ pc). It follows that an observer must be careful not to interpret the stellar mass function and binary proportion of such populations in terms of a possible dependence of these quantities on star-formation environment, without due consideration of the dynamical history.

3.4. Binding energy, period and mass ratio

Only binaries that are sufficiently bound will not be ionised when they suffer a close interaction with another system, after which they may leave the aggregate with relatively high velocity. Thus, the correlation between binary star binding energy, $E_{\text{bin}}$, and its centre of mass kinetic energy, $E_{\text{kin}}$, indicates the history of a system.

Above it was seen that the final binary proportion, $f_v$, for systems with $2$ km/s $< v < 30$ km/s, is larger for initially more concentrated binary star aggregates. It can achieve values of 20-40 per cent for $R_{0.5} \leq 0.25$ pc, although the overall final binary proportion is small ($f_{\text{tot}} \approx 0.27$, fig. 3 in Kroupa 1995a). This result is relevant for the distribution of young stars around star-forming regions. Initially highly concentrated embedded clusters may add young binaries to regions as far as 300 pc over a period of 10 Myr. Such binaries have a well-defined correlation between $E_{\text{bin}}$ and $E_{\text{kin}}$. This correlation transforms to correlations between $P$ and $v$, between the mass ratio ($q = m_2/m_1 \leq 1$) and $v$, and between the system mass ($m_1 + m_2$) and $v$, where $m_1$ and $m_2$ are the primary- and secondary-star masses, respectively.

3.4.1. Binding energy and period

In Figs. 3 and 4 are plotted $E_{\text{bin}}$ against $E_{\text{kin}}$, as well as the orbital period, $P$, against ejection velocity, $v$, for each binary system in the $N_{\text{run}}$ simulations. The distribution of data points for the $R_{0.5} = 2.5$ pc aggregate (top two panels in Fig. 3) reflects approximately the initial distribution in binding energies ($\log_{10} E_{\text{bin}} > 2$) and orbital periods ($\log_{10} P \geq 3$). Only very few binaries have gained binding energy and/or have been accelerated to higher velocities. As the initial $R_{0.5}$ is reduced, the number of binary systems with hardened orbits and larger $v$ increases. The depletion of orbits at large $P$ is clearly evident in the $R_{0.5} = 0.08$ pc cluster.

Figs. 3 and 4 nicely show that a binary with an orbital period corresponding to $v_{\text{orb}}$ only remains bound when suffering a collision, if the ejection velocity $v < v_{\text{orb}}$. A single notable exception, that occurred in the five simulations of the $R_{0.5} = 0.08$ pc aggregate, is the binary system with $P = 10^{5.7}$ d and $v = 16$ km/s. It is difficult to trace the detailed dynamical history of any individual stellar system owing to the discrete output times when stellar masses, positions and velocities are written to computer disk. But this binary probably formed in a complex high-order interaction, that resulted in two stars being ejected on essentially
identical trajectories.

The results discussed so far are valid for a primordial binary star population that has periods $P > 10^3$ d. In reality, binaries with shorter periods do exist with a binary proportion $f \approx 0.15$ (fig. 1 in Mathieu 1994). The inclusion of primordial binaries with $P < 10^3$ d does not change the results presented here, apart from slightly increasing $f_v$ for the ejected systems. In Figs. 3 and 4, both the $(E_{\text{bin}}, E_{\text{kin}})$ and $(\log_{10} P, v)$ plots would contain orbits with $E_{\text{bin}} > 10^2 M_\odot \text{km}^2/\text{s}^2$ and $P < 10^3$ d, and an upper envelope for $v > 1 \text{ km/s}$ given by the dashed diagonal lines.

The correlation between binding and kinetic energy is established particularly well for the binary systems that are formed by capture in the single star aggregates (Fig. 5). Their periods range from $P > 100$ d to $10^{11}$ d. The binary systems with $P \approx 10^{10}$ d form by chance three-body low-velocity encounters and form a distinct group in the figure.

3.4.2. Mass ratio and system mass

More massive systems have a higher binding energy, and are thus more resistant to higher accelerations. Binaries that are ejected from an aggregate should thus have a larger system mass and a mass-ratio nearer to unity for higher $v$.

In Figs. 6 and 7, $m_1 + m_2$ and $q$ are plotted in dependence of $v$ for the binary-star aggregates. The $R_{0.5} = 2.5$ pc aggregate shows approximately the initial distributions, and is useful as a reference. As the aggregate concentration is reduced, the number of ejected systems increases. These tend to have larger system masses, as expected. At the same time, binary stars with a mass-ratio $q < 0.2$ are preferentially removed as $R_{0.5}$ is reduced. This is expected because, for a given semi-major axis, they have the lowest binding energy, $E_{\text{bin}} \propto m_1^2 \times q$. The correlation between $q$ and $v$ is in the expected sense, which is evident in the figures by the appearance of orbits in the region $q > 0.6, v > 2 \text{ km/s}$. However, the correlation is weak, because $E_{\text{bin}}$ also depends on $m_1$. As is evident from the figures, the number of binaries with $m_1 + m_2 > 1.5 M_\odot$ increases for smaller $R_{0.5}$. This is because the more frequent three-body and higher-order interactions lead to more frequent exchanges of companions, which most often leads to the production of binary systems consisting of the most massive stars involved in the interaction (Harrington 1975, Heggie 1975, Hills 1977, see also Valtonen & Mikkola 1991, McDonald & Clarke 1993).

Concerning the single-star aggregates, Fig. 8 shows that the distribution of mass ratios of the dynamically formed binaries in the $R_{0.5} = 0.25$ pc aggregate is roughly flat over the whole accessible range. In the more concentrated aggregate, binaries form with larger system mass and a bias towards larger $q$, which is a result of dynamical biasing discussed in greater detail by McDonald & Clarke (1993).

4. Conclusions

The correlations between ejection velocity and the proportion of binaries, as well as their orbital parameters, have been quantified for a range of initial dynamical configurations. The correlations are useful in the study of stellar systems that are apparently ejected from Galactic clusters (see e.g. Frink et al. 1997), some of which are known to be rich in binaries (e.g. Raboud & Mermilliod 1998a, 1998b). Observed ejected binaries should show correlations as presented in Figs. 3, 4, 7, and 8. The results for the binary-rich aggregates modelled here are also relevant for an understanding of the large-scale distribution of young stars, because
most stars appear to form in aggregates with a high binary proportion. Additionally, the correlations contain information about the dynamical configuration at birth.

For binary-rich aggregates containing a few hundred stars the following correlations result: (i) more tightly clustered aggregates lead to more stellar systems having larger ejection velocities and a smaller overall binary proportion, (ii) the large population of primordial binaries leads to a significantly enhanced number of systems with high-ejection velocities compared to single-star aggregates, (iii) systems with high ejection velocities have a significantly reduced binary proportion, (iv) binary stars with high ejection velocities have short-period orbits, and tend to be more massive with a mass-ratio biased towards unity, (v) the average system mass as a function of ejection velocity is defined above about 2 km/s by stochastic close encounters, so that systems more massive than 0.5 $M_\odot$ with high ejection velocities occur, and (vi) aggregates with $R_{0.5} \leq 0.25$ pc lead to a complex dependence of the resulting binary proportion on velocity, whereas a stellar population emerging from less concentrated aggregates shows a monotonic decrease of the binary proportion with increasing velocity.

For aggregates of a few hundred single stars one obtains: (i) more tightly clustered aggregates lead to an increased number of stellar systems with larger ejection velocities (but significantly less so than in the binary-rich aggregates), and an enhanced overall binary proportion that remains significantly below the observed binary proportion in the Galactic field, (ii) the binary proportion increases with ejection velocity, (iii) as (iv) above, and (iv) is as (v) above.

Remnant unbound young populations take long to disperse because they have a small velocity dispersion. The binary proportion and mean system mass (and thus the inferred IMF) of such a remnant population, sensitively depends on the initial dynamical configuration of the binary-rich birth aggregate. After emerging from the birth aggregate, the distribution of velocities of a young stellar population changes with time in the gravitational potential of the nearby molecular clouds. A substantial proportion of emerging stars is likely to remain bound to the parent molecular cloud until it ceases to exist.

These findings are important for interpreting the spatial distribution, kinematics and binarity of young stars within and surrounding star-forming regions. Molecular clouds, in which stars form preferentially in dense embedded binary-rich clusters, should have an enhanced halo population of ejected and relatively binary poor ($f \approx 0.25$) young stellar systems. Also, young but binary-depleted groups of stars can be misinterpreted to be evidence for an environmental dependency of the binary-formation mechanism. For example, in fig. 6 of Brandner et al. (1996), the region US-B has more binaries than the region US-A, which also contains many more B stars than US-B. The presence of B stars suggests that the stars in US-A may have formed in dense embedded clusters. The stars seen in US-A would then constitute the $v \lesssim 1$ km/s remnant population for $R_{0.5} \lesssim 0.25$ pc (Fig. 6). Given the results of the present study, it is suggested that such a difference in binary proportion between two regions may be due to different initial dynamical configurations, and need not imply a dependence of the binary proportion on the star-forming environment.

Important for the interpretation of the large-scale distribution of young stars surrounding star forming sites is the realisation that relatively massive systems are ejected with relatively large velocity (2–30 km/s, Fig. 6), which is a point also stressed by Sterzik & Durisen (1995). The X-ray surveys are flux limited and detect the massive stars (Wichmann et al. 1996), the presence of which around star-forming regions may be a natural consequence of the processes studied here. However, if some young binary systems are found to have orbital periods that place them above the dashed lines in the right panels of Figs. 3–5, then this would support the suggestion by Feigelson (1996), that some star-formation occurs in small high-velocity clouds.
Acknowledgements

I am very grateful to Sverre Aarseth for allowing me to use his NBODY5 programme, and I thank Rainer Spurzem and Mirek Giersz for helpful discussions.

REFERENCES

Aarseth S.J., 1994, in Contopoulos G., Spyrou N. K., Vlahos L., eds, Galactic Dynamics and N-Body Simulations. Springer, Berlin, p.277
Aarseth S.J., Hills J.G., 1972, A&A, 21, 255
Armitage P.J., Clarke C.J., 1997, MNRAS, 285, 540
Boss J.P., 1995, RevMexAA, 1, 165
Bonnell I., Kroupa P., 1998, in The Orion Complex Revisited, M.J. McCaughrean, A. Burkert (eds), ASP Conference Series, in press [astro-ph/9802306]
Brandner W., Alcala J.M., Kunzel M., Moneti A., Zinnecker H., 1996, A&A, 307, 121
Clarke C.J., 1996, in Evolutionary Processes in Binary Stars, NATO ASI, R.A.M. J. Wijers, M.B. Davies, C.A. Tout eds, Kluwer, Dordrecht, p. 31
Clarke C.J., Pringle J.E., 1992, MNRAS, 255, 423
Conlon E.S., Dufton P.L., Keenan F.P., Leonard P.J.T., 1990, A&A, 236, 357
Duquennoy A., Mayor M., 1991, A&A, 248, 485
Durisen R.H., Sterzik M.F., 1994, A&A, 286, 84
Feigelson E.D., 1996, ApJ, 468, 306
Frink S., Röser S., Neuhäuser R., Sterzik M.F., 1997, A&A, 325, 613
de la Fuente Marcos R., 1997, A&A, 322, 764
Ghez A.M., McCarthy D.W., Patience J.L., Beck T.L., 1997, ApJ, 481, 378
Gies D.R., Bolton C.T., 1986, ApJS, 61, 419
Gorti U., Bhatt H.C., 1996, MNRAS, 278, 611
Harrington R.S., 1975, AJ, 80, 1081
Heggie D.C., 1975, MNRAS, 173, 729
Heggie D.C., Rasio F.A., 1996, MNRAS, 282, 1064
Hillenbrand L.A., Hartmann L.W., 1998, ApJ, 492, 540
Hills J.G., 1986, MNRAS, 278, 540
Hills J.G., 1977, AJ, 82, 626
Hut P., 1983, ApJ, 272, L29
Köhler R., Leinert Ch., 1998, A&A, 331, 977
Kroupa P., 1995a, MNRAS, 277, 1491
Kroupa P., 1995b, MNRAS, 277, 1507
Kroupa P., 1995c, MNRAS, 277, 1522
Kroupa P., Tout C. A., Gilmore G., 1993, MNRAS, 262, 545
Kiseleva L.G., Eggleton P.P., Orlov V.V., 1994, MNRAS, 270, 936
Lada C.J., Lada E.A., 1991, in The Formation and Evolution of Star Clusters, K. Janes, ed., ASP Conf. Series 13, p.3
Leinert Ch., Zinnecker H., Weitzel N., Christou J., Ridgway S. T., Jameson R., Haas M., Lenzen R., 1993, A&A 278, 129
Leonard P.J.T., 1991, AJ, 101, 562
Leonard P.J.T., 1995, MNRAS, 277, 1080
Leonard P.J.T., Duncan M.J., 1990, AJ, 99, 608
Mathieu R.D., 1994, ARA&A, 32, 465
McDonald J.M., Clarke C.J., 1993, MNRAS, 262, 800
McDonald J.M., Clarke C.J., 1995, MNRAS, 275, 671
Padgett D.L., Strom S.E., Ghez A.M., 1997, ApJ, 477, 705
Petr M.G., du Foresto V.C., Beckwith S.V.W., Richichi A., McCaughrean M.J., 1998, ApJ, in press
Prosser C. F., Stauffer J. R., Hartmann L., Soderblom D. R., Jones B. F., Werner M. W., McCaughrean M. J., 1994, ApJ, 421, 517
Raboud D., Mermilliod J.-C., 1998a, A&A, 329, 101
Raboud D., Mermilliod J.-C., 1998b, A&A, in press (astro-ph/9802284)
Scalo J., 1986, Fund. Cosmic Physics, 11, 1
Simon M., Ghez A.M., Leinert Ch., et al., 1995, ApJ, 443, 625
Sterzik M.F., Durisen R.H., 1995, A&A, 304, L9
Tout C.A., 1991, MNRAS, 250, 701
Trimble V., 1990, MNRAS, 242, 79
Valtonen M., Mikkola S., 1991, ARA&A, 29, 9
Wichmann R., Krautter J., Schmitt J.H.M.M., Neuhäuser R., Alcalá J.M., Zinnecker H., Wagner R.M., Mundt R., Sterzik M.F., 1996, A&A, 312, 439
| \( \log_{10} v \) [km/s] | \( R_{0.5} \) [pc] = 2.5 | 0.8 | 0.25 | 0.08 | 0.25* | 0.08* |
|-------------------|------------------|-----|-----|-----|-------|-------|
| -1.925            | 0                | 0   | 0   | 0.13| 0    | 0.09  |
| -1.775            | 0                | 0   | 0.07| 0.06| 0    | 0.09  |
| -1.625            | 0.09             | 0   | 0   | 0.06| 0    | 0.34  |
| -1.475            | 0.09             | 0.08| 0   | 0.32| 0.17 | 0.77  |
| -1.325            | 0.37             | 0.24| 0.14| 0.95| 0.77 | 2.73  |
| -1.175            | 0.64             | 0.73| 1.61| 2.98| 1.36 | 4.26  |
| -1.025            | 2.48             | 1.61| 3.09| 6.29| 3.66 | 10.22 |
| -0.875            | 3.59             | 4.12| 6.31| 11.37| 7.40 | 17.12 |
| -0.725            | 8.19             | 7.34| 10.80| 12.70| 14.20| 19.34 |
| -0.575            | 13.89            | 11.78| 16.83| 13.14| 20.32| 16.78 |
| -0.425            | 19.04            | 19.21| 16.97| 13.52| 21.09| 11.50 |
| -0.275            | 19.96            | 19.69| 14.03| 9.59 | 14.97| 5.96  |
| -0.125            | 14.35            | 13.24| 9.05 | 6.86 | 8.16 | 2.64  |
| +0.025            | 7.82             | 8.15| 4.98 | 5.46 | 2.55 | 2.90  |
| +0.175            | 2.39             | 3.63| 3.09 | 3.30 | 2.30 | 1.87  |
| +0.325            | 2.12             | 2.82| 3.51 | 3.37 | 1.19 | 1.45  |
| +0.475            | 0.74             | 1.86| 2.73 | 2.60 | 0.51 | 0.94  |
| +0.625            | 1.66             | 1.45| 2.52 | 2.67 | 0.51 | 0.26  |
| +0.775            | 1.20             | 1.69| 1.61 | 1.97 | 0.60 | 0.17  |
| +0.925            | 0.37             | 0.89| 1.19 | 1.08 | 0.17 | 0.51  |
| +1.075            | 0.55             | 0.65| 0.77 | 0.70 | 0.09 | 0.09  |
| +1.225            | 0.37             | 0.32| 0.42 | 0.44 | 0    | 0     |
| +1.375            | 0               | 0.32| 0.14 | 0.13 | 0    | 0     |
| +1.525            | 0               | 0.16| 0.14 | 0.25 | 0    | 0     |
| +1.675            | 0.09            | 0   | 0   | 0.06 | 0    | 0     |

Table 1: Velocity distributions.  \( R_{0.5} \) is for the two single-star aggregates.
Fig. 1.— Binary proportion, $f_v$, as a function of velocity, $v$, for the aggregates with $R_{0.5} = 2.5, 0.77, 0.25$ and 0.077 pc (solid histogram). Solid circles are the mean system mass, $<m>_v$. Error-bars are Poisson uncertainties. Long-dashed curves represent the distribution of velocities, $h_v$, plotted in arbitrary ordinate units and tabulated in Table 1. Horizontal dashed lines mark the rough one-sigma range of the binary proportion for G-, K-, and M-main sequence systems in the Galactic field ($f_{\text{tot}}^\text{obs} = 0.47 \pm 0.05$, Kroupa 1995a). From the value of $f_v$ around the maximum of $h_v$, as well as the shape of the period and mass-ratio distributions, it is deduced that $0.25 \text{ pc} < R_{0.5} < 0.8 \text{ pc}$ are solutions to inverse dynamical population synthesis (Kroupa 1995a).
Fig. 2.— As Fig. 1 but for stellar aggregates that initially contain no binary system.
Fig. 3.— Distribution of orbits in the binding-energy–kinetic-energy plane (left panels) (energy units are $M_\odot$ km$^2$/s$^2$) and the period–velocity plane (right panels) for the two binary-star aggregates with $R_{0.5} = 2.5$ pc and 0.77 pc. Orbits along the diagonal dashed line have a binding energy that is equal to the kinetic energy. The region between the two vertical dashed lines for $R_{0.5} = 2.5$ pc and $R_{0.5} = 0.08$ pc (Fig. 4) contains 95 per cent of all initial kinetic energies. The vertical dotted line plotted for these two aggregates approximates $E_{\text{kin}}$. Orbits with $E_{\text{bin}}/E_{\text{kin}} > 1$ are termed hard and are less likely to be ionised. Dashed lines in the right panels are equation 4 for $m_{\text{sys}} = 2.2 M_\odot$ (upper line) and $m_{\text{sys}} = 0.2 M_\odot$ (lower line). The vertical dotted lines are the initial velocity dispersions.
Fig. 4.— As Fig. 3 but for the two binary-star aggregates with $R_{0.5} = 0.25$ pc and 0.08 pc.
Fig. 5.— As Fig. 3 but for the two single-star aggregates with $R_{0.5} = 0.25$ pc and 0.08 pc.
Fig. 6.— Distribution of orbits in the system-mass–velocity plane (left panels) and the mass-ratio–velocity plane (right panels) for the two binary-star aggregates with $R_{0.5} = 2.5$ pc and 0.77 pc. The system mass is $m_1 + m_2$ and the mass ratio is $q = m_2/m_1 \leq 1$, where $m_1$ and $m_2$ are the primary- and secondary star masses, respectively. The vertical dotted lines indicate the initial velocity dispersion.
Fig. 7.— As Fig. 6 but for the two binary-star aggregates with $R_{0.5} = 0.25$ pc and 0.08 pc.
Fig. 8.— As Fig. 6 but for the two single-star aggregates with $R_{0.5} = 0.25$ pc and 0.08 pc.