DYNAMICS OF OPEN STAR CLUSTERS

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ABSTRACT

The dynamical evolution of open star clusters has been studied successfully by numerical N-body simulations. We compare in detail the theoretically predicted lifetimes with those derived from the observed age distribution of open clusters. Rare but efficient encounters between clusters and giant molecular clouds are probably responsible for the sudden disruption of many open clusters. Massive black holes from the galactic corona would, on the average, affect only old open clusters.

1. INTRODUCTION

Our theoretical knowledge of the dynamical evolution of open star clusters stems largely from numerical N-body simulations. In such simulations, the orbits of all the stars in the cluster are followed numerically by integrating the equations of motions of the complete N-body problem. In addition to the mutual gravitational interactions between all the stars in the cluster, other important effects, such as the stationary tidal field of the Galaxy, the impulsive tidal fields of passing interstellar clouds, the mass loss of evolving stars etc., can be easily implemented into the numerical experiments in a very realistic manner. With modern computers and the available sophisticated integration schemes, it is not difficult to follow the evolution of a star cluster with an initial membership of N = 1000 stars over its total lifetime, i.e. until the cluster is nearly completely dissolved. For the application of the results of the numerical N-body simulations to real astronomical objects, it is, of course, important to know the correct physical input data, such as initial conditions, mass spectrum of the stars, masses and radii of passing interstellar clouds etc. . This limitation is, however, also valid for any other theoretical treatment of the problem.

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The results of the N-body simulations for open star clusters have been reviewed in the last decade by Wielen (1974, 1975), Aarseth and Lecar (1975) and Aarseth (1984). E.Terlevich (1980, 1983) has carried out an important series of new N-body simulations for open clusters. Her results confirm most of the conclusions drawn in the earlier reviews from less extensive material. Instead of repeating the reviews listed above, we shall concentrate in the present paper on some new results, mainly concerning the effects of passing massive objects on the life-times of open clusters.

In contrast to the numerical N-body simulations, statistical theories of stellar dynamics are difficult to apply to the internal dynamics of open clusters. This is due to the relatively small number of stars in an open cluster, typically between N = 100 and N = 1000. Firstly, statistical theories assume by their very nature 'large' N, and it is uncertain wether a typical open cluster fulfills already this requirement. Secondly, in open clusters, the crossing time T_{cr} and the internal relaxation time T_{rel} are of same order of magnitude, thereby hampering a conventional statistical treatment as used for globular star clusters with their much higher values of N. King (1980) has emphasized these difficulties in his review of the dynamics of open clusters. A statistical treatment is, however, rather suitable for studying the effects of passing interstellar clouds etc. on open cluster (Section 3), since these external effects are basically independent of the number N of stars in the cluster.

2. CLUSTER LIFETIMES DERIVED FROM THE OBSERVED AGE DISTRIBUTION

A comparison of the total lifetimes of clusters derived from the observed age distribution with theoretically predicted disintegration times seems to be the most powerful observational test of dynamical theories of open clusters (Wielen 1971, 1974, 1975). The age distribution of open clusters has been recently rediscussed by van den Bergh (1981), Janes and Adler (1982) and Lynga (1982a, b, 1983). Especially the observed age distribution derived by Lynga (1982b) from a very extensive material is in perfect agreement with that derived earlier by Wielen which led to the following conclusions about the 'observed' total lifetimes of open clusters (Wielen 1971): 50% of newly born clusters disintegrate within $2\cdot10^8$ years (median lifetime of open clusters), 10% have a total lifetime longer than $5\cdot10^8$ years, and only 2% live longer than $1\cdot10^9$ years. Hence the typical lifetime of an open cluster is short, but there exists a wide spread in individual lifetimes.

According to van den Bergh and McClure (1980), Janes and Adler (1982) and Lynga (1982a, b, 1983), open clusters in the outer parts of the Galaxy ($R > R_0$) have longer lifetimes than those in the inner parts ($R < R_0$).

3. ENCOUNTERS BETWEEN CLUSTERS AND MASSIVE OBJECTS

Encounters of open clusters with passing massive objects can reduce, or even determine, the lifetimes of the clusters. Spitzer (1958) discussed the effect of interstellar HI clouds on open clusters. We shall derive here the effects of more massive objects, such as giant molecular clouds (GMC) or massive black holes (BH). GMCs certainly exist in our Galaxy, and van den Bergh and McClure (1980) proposed already that GMCs may strongly affect the lifetimes of open clusters. Massive black holes may constitute the 'dark matter' in the galactic corona. Ostriker (1983) has pointed out that the existence of such black holes would nicely explain the observed age-velocity relation of disk stars (Wielen 1977). Lacey (1984) has used this idea to calculate the typical mass of such coronal black holes.

3.1 General Theory

We shall use basically the formalism developed by Spitzer (1958) for deriving the disruption time of clusters due to passing objects. In the impulsive approximation, the increase ΔE_c in the total energy of a cluster (index c), due to the tidal field of a passing object (index n), is given by

$$\Delta E_c = (4\alpha^2/3)\ (Gm_n/(p^2V))^2\ m_c r_c^2 \quad , \qquad (1)$$

where m_c is the mass of the cluster, r_c the median radius of the cluster (containing half of m_c in projection), α the ratio between the root-mean-square cluster radius and r_c, G the gravitational constant, and m_n the mass of the object (GMC, BH) which moves relative to the cluster center on a straight line with constant velocity V and shortest distance p (impact parameter). Eq.1 overestimates ΔE_c, if $p < r_n$ (GMC) or if $p < r_c$. In these cases, $p < \max(r_n, r_c)$, we calculate ΔE_c by replacing p in Eq.1 by

$$p_0 = \max(r_n, r_c) \quad . \qquad (2)$$

This approximation is sufficient for our purpose. For a Plummer model, the total energy E_c of the cluster is given by

$$E_c = -(3\pi/64)\ Gm_c^2/r_c \quad . \qquad (3)$$

We ask now for that impact parameter p_1 for which ΔE_c is already equal to $-E_c$ after just one passage of an object. From Eqs.1 and 3, we get

$$p_1 = 4(\alpha/3)^{1/2}(G/\pi)^{1/4} m_n^{1/2} V^{-1/2} (m_c/r_c^3)^{-1/4} \quad . \qquad (4)$$

3.1.1 The Case $p_1 > p_0$

If $p_1 > p_0$, then a single passage of an object with $p < p_1$ is able to disrupt the cluster immediately. The average number Z of such encounters with $p < p_1$ in a period Δt is

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$$Z = \pi p_1^2 \nu_n V \Delta t \qquad , \qquad (5)$$

where ν_n is the number density of the objects. We get an estimate for the time T_1 after which a cluster is disrupted by a single encounter with a massive object, if we set $Z = 1$ and $\Delta t = T_1$ in Eq.5 and insert p_1 from Eq.4:

$$T_1 = (3/(16\alpha))\pi^{-1/2}(Gm_c/r_c^3)^{1/2}/(G\rho_{an}) \qquad , \qquad (6)$$

where

$$\rho_{an} = m_n \nu_n \qquad (7)$$

is the overall mass density of the objects (GMCs or BHs). It is remarkable that T_1 does not depend on the individual mass m_n of the passing objects but only on ρ_{an}. Furthermore, T_1 is independent of the velocity V of the passing objects.

A short calculation shows that all the distant encounters with $p > p_1$ increase the total energy of the cluster just by $-E_c$ within the period T_1, if we neglect the increase of αr_c due to successive encounters and the adiabaticity of very distant encounters. Since the distant encounters ($p > p_1$) dissolve the cluster within the same period T_1 as the close encounters ($p < p_1$), the total dissolution time scale $T_{n,1}$ due to the combined effect of close and distant encounters is approximately given by

$$T_{n,1} = T_1/2 \qquad (8)$$

with T_1 according to Eq.6. This shortening of the time scale by a factor of two has been experimentally confirmed by Bahcall et al. (1984) for the disruption of wide binaries.

The dissolution of clusters due to close encounters ($p < p_1$) with massive objects introduces a strong accidentalness into the lifetimes of open clusters. Even the effect of distant encounters ($p > p_1$) is governed by a few encounters with $p \sim p_1$ because of the strong decrease of the energy transfer with increasing p. Hence the lifetime of an individual cluster can significantly deviate from its expectation value, $T_{n,1}$, given by Eq.8.

3.1.2 The Case $p_1 < p_0$

If $p_1 < p_0$, then a number of successive encounters are necessary for disrupting the cluster. This condition has been implicitely assumed by Spitzer (1958). The rate of change of E_c is given by Eq.1 multiplied by the number of collisions per unit time and per interval of p, and integrated over p:

$$\dot{E}_c = (4\alpha^2/3)\ G^2 m_n^2 \nu_n V^{-1} m_c r_c^2 \left(\int_0^{p_0} 2\pi p p_0^{-4} dp + \int_{p_0}^{\infty} 2\pi p p^{-4} dp \right)$$

$$= (8\pi\alpha^2/3)\ G^2 m_n \rho_{an} V^{-1} m_c r_c^2 p_0^{-2} \quad . \tag{9}$$

If we neglect the increase in αr_c due to successive encounters, we obtain an estimate for the dissolution time $T_{n,0}$ of the cluster from $-E_c/\dot{E}_c$, using Eqs.3 and 9:

$$T_{n,0} = (9/(512\alpha^2))\ G^{-1} m_n^{-1} \rho_{an}^{-1}\ V\ m_c r_c^{-3} p_0^2 \quad , \tag{10}$$

where p_0 is either r_n or r_c according to Eq.2.

If we had taken into account the increase in αr_c due to successive encounters by using Eq.1 and integrating over t until $E_c = 0$ (Spitzer 1958), we would have found $T_{n,0}/3$ for the dissolution time scale instead of $T_{n,0}$. We prefer, in accordance with Spitzer and Chevalier (1973), to use $T_{n,0}$ as a more conservative estimate. Equation 9 overestimates probably the real increase of E_c, because the outermost stars in a cluster gain energy so rapidly that they often escape before sharing their energy gain with the remaining cluster by encounters with other stars in the cluster. Furthermore, $T_{n,0}$ according to Eq.10 equals then $T_{n,1}$ in the limit $p_0 = p_1$. The disruption time t_d, derived by Spitzer (1958), is twice as long as $T_{n,0}/3$, because he neglected in that paper encounters with $p < p_0$.

Why is $T_{n,0}$ not also valid for $p_1 > p_0$? The reason is the following: For $p_1 > p_0$, each encounter with $p < p_1$ has an 'overkill' capacity, i.e. ΔE_c is larger than $-E_c$. The overshooting parts of these energy gains must not be used in calculating the average energy change $\dot{E}_c$. In order to take into account the upper limit $-E_c$ for ΔE_c, we have to replace p_0 by p_1 in Eqs.9 and 10 for $p_1 > p_0$. By replacing p_0 by p_1 in Eq.10 for $T_{n,0}$, we recover in fact $T_{n,1}$ derived in Section 3.1.1 (Eq.8).

3.1.3 Other Aspects

If a cluster is exposed to an ensemble of passing objects with different values of m_n, r_n and V, some encounters belong to the case $p_1 > p_0$, while others correspond to $p_1 < p_0$. For simplicity, we shall use then either $T_{n,1}$ or $T_{n,0}$, according to the majority of the efficient encounters. In all of our applications, we assume furthermore $\alpha = 1$.

In calculating the disruption times $T_{n,1}$ and $T_{n,0}$, we have neglected the effect of the stationary tidal field of the Galaxy. Due to this galactic tidal field, the real dissolution times will be shorter than given here. The effect is, however, small for typical open clusters for which the median radius r_c is much smaller than the tidal radius (Bouvier 1971).

As pointed out by Spitzer (1958), slow or distant encounters may not be impulsive. The impulsive approximation is valid only for encounters with

$$p < p_{ad} = V\,T_{cr} \qquad (11)$$

i.e. the internal crossing time T_{cr} of the cluster should be longer than the effective duration of the encounter, p/V. Due to the strong decrease of ΔE_c with increasing p, our earlier results are essentially correct as long as

$$\max(p_0,p_1) < p_{ad} \qquad (12)$$

holds.

The general theory for encounters between open clusters and massive objects has many similarities to the problems of the disruption of wide binaries (Bahcall, Hut, and Tremaine 1984) and of the dissolution of the Oort Comet Cloud (e.g. Bailey 1983). There are, however, also important differences. For example, a wide binary can be disrupted by a very close encounter between one component and a passing compact object (e.g. a star), while for open clusters, the effect of encounters with $p < r_c$ on the dissolution of the whole cluster are essentially independent of p.

3.2 Giant Molecular Clouds

Observations indicate for a typical giant molecular cloud (GMC) a mass of $m_n = 5\cdot10^5\ m_\odot$ and a diameter of $2r_n = 50$ pc. The contribution of GMCs to the overall mass density in the solar neighbourhood, i.e. at $R = R_0$, is rather uncertain. We shall use $\rho_{an} = 0.02\ m_\odot/pc^3$, perhaps a somewhat optimistic value. The typical velocity V of a young cluster relative to a GMC is about 10 km/s. Since r_n is larger than r_c for open clusters, p_0 is equal to r_n. From Eq.4, we obtain that the disruption of the cluster by a single passage of a GMC is possible ($p_1 > p_0 = 25$pc), if

$$m_c/r_c^3 < 250\ m_\odot/pc^3 \quad . \qquad (13)$$

Many open clusters belong to this class. The disruption time of the cluster due to the GMCs is then given by

$$T_{n,1} = 6.2\cdot10^8 \text{ years } ((m_c/r_c^3)/250\ m_\odot pc^{-3})^{1/2} \quad . \qquad (14)$$

For clusters which are denser than the limit set by Eq.13, the longer disruption time $T_{n,0}$ applies.

For the effect of GMCs on open clusters, the overall mass density ρ_{an} is of primary importance, because this is the only property of clouds which enters into the disruption time $T_{n,1}$. Even much smaller masses m_n of the clouds would not alter our conclusions if ρ_{an} is kept fixed and if $p_1 > p_0$ still holds. For example, we can allow molecular clouds with $m_n = 2 \cdot 10^4\ m_\odot$ and $2r_n = 10$ pc, because even then many open clusters will belong to the case $p_1 > p_0 = r_n = 5$ pc ($p_1 > 5$ pc for $m_c/r_c^3 < 250\ m_\odot/pc^3$).

The effect of encounters between open clusters and GMCs depend on the overall density ρ_{an} of GMCs at the position of the cluster. Hence older clusters with higher distances z from the galactic plane suffer less from GMCs. Furthermore, the average space velocity of older clusters is higher, thereby decreasing p_1 and hence shifting some of these clusters from the case $p_1 > p_0$ to $p_1 < p_0$.

The adiabatic limit for p is given by

$$p < p_{ad} = 100 \text{ pc } (V/10 \text{ kms}^{-1})\ (T_{cr}/10^7 \text{ years}) \qquad (15)$$

with the internal crossing time of the cluster (using a Plummer model)

$$T_{cr} = (32/(3\pi))^{3/2} (Gm_c/r_c^3)^{-1/2}$$
$$= 5.9 \cdot 10^6 \text{ years } (250\ m_\odot pc^{-3}/(m_c/r_c^3))^{1/2} \quad . \qquad (16)$$

Hence the impulsive approximation is not valid anymore for encounters between GMCs and open clusters with $m_c/r_c^3 > 600\ m_\odot/pc^3$, because then $p_0 = r_n > p_{ad}$ holds.

3.3 Massive Coronal Black Holes

The local density of the invisible galactic corona is $\rho_{an} = 0.006\ m_\odot/pc^3$, according to the galactic mass model constructed by Caldwell and Ostriker (1981). Lacey (1984) derives the quantity $\nu_n m_n^2 = \rho_{an} m_n = 2 \cdot 10^4\ m_\odot^2 pc^{-3}$ for the postulated coronal black holes. Using ρ_{an} from Ostriker and Caldwell, we find for the typical mass of a coronal black hole $m_n = 3 \cdot 10^6\ m_\odot$. The relative velocity between a cluster and a black hole should be typically of the order of V = 250 km/s. For black holes, we have $r_n \sim 0$ and hence always $p_0 = r_c$. The limiting impact parameter p_1 for the coronal black holes is given by

$$p_1 = 12 \text{ pc } (250\ m_\odot pc^{-3}/(m_c/r_c^3))^{1/4} \quad . \qquad (17)$$

Hence, most open clusters belong to the case $p_1 > p_0 = r_c$. For these open clusters, the disruption time of the cluster due to coronal black holes is given by

$$T_{n,1} = 2.1 \cdot 10^9 \text{ years } ((m_c/r_c^3)/250\ m_\odot pc^{-3})^{1/2} \quad . \qquad (18)$$

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The rather long time scale $T_{n,1}$ shows that coronal black holes affect, on the average, only old open clusters. The encounters between open clusters and coronal black holes are nearly always impulsive, because the adiabatic limit p_{ad} (Eqs.11 and 15) is typically of the order of 1 kpc, i.e. $p_1 << p_{ad}$.

4. LIFETIMES OF OPEN CLUSTERS

We shall now discuss the theoretically predicted dissolution times of open clusters and compare these predictions with the 'observed' lifetimes derived from the age distribution (Section 2).

First, we consider a 'typical' open star cluster. We assume for such a typical cluster at birth N = 500 stars (with a realistic spectrum of stellar masses) and a total initial mass of $m_c = 250\ m_\odot$ (see Lynga (1983) and Bruch and Sanders (1983)). In Figure 1, we illustrate the total lifetime T of such a cluster as a function of the median radius r_c of the whole cluster (r_c encircles $m_c/2$ or N/2 in projection). For $r_c < 0.1$ pc, the cluster is essentially isolated and evaporates due to internal relaxation (encounters between cluster stars) on a time scale shorter than $2 \cdot 10^8$ years. For $r_c > 0.1$ pc, the stationary tidal field of the Galaxy enhances the dissolution with respect to isolated systems significantly. In the range 0.5 pc < r_c < 3 pc, the total lifetime, measured in years, depends then only weakly on r_c. The full curve and the symbols in Figure 1 represent results from N-body simulations which include the galactic tidal field. There is beautiful agreement between the N-body simulations of Terlevich (1983, e.g. model IV) and Wielen (1975, e.g. model FG3). The presence of initial binaries (Aarseth 1980) and the mass loss of evolving stars seem to affect the lifetimes of clusters only marginally.

The tidal radius ξ_L of a cluster (King 1962) in the direction towards the galactic center is given by

$$\xi_L = (\ Gm_c/(4A(A-B))\ )^{1/3} \quad . \tag{19}$$

The tidal limits in the other two directions are smaller, $\eta_L = (2/3)\xi_L$ and $\zeta_L \sim 0.5\ \xi_L$ (Wielen 1974, Fig.6). Clusters with median radii $r_c \gtrsim 0.5\ \xi_L$ are already unbound in the gravitational tidal field of the Galaxy and expand on the time scale of the galactic rotation, $T_{rot} = 2\pi/\omega_0 = 2\pi/(A-B) = 2.5 \cdot 10^8$ years.

The disruption time of an open cluster due to passing interstellar HI clouds (dashed line in Fig.1) is proportional to r_c^{-3} for a given m_c (Eq.10). It has been predicted by Wielen(1974, 1975) on the basis of Spitzer's impulsive approximation that the disruption of open clusters is significantly accelerated by passing interstellar HI clouds of the standard type only if the cluster is already either weakly bound or even unstable because of the galactic tidal field (i.e. $r_c > 3$ pc

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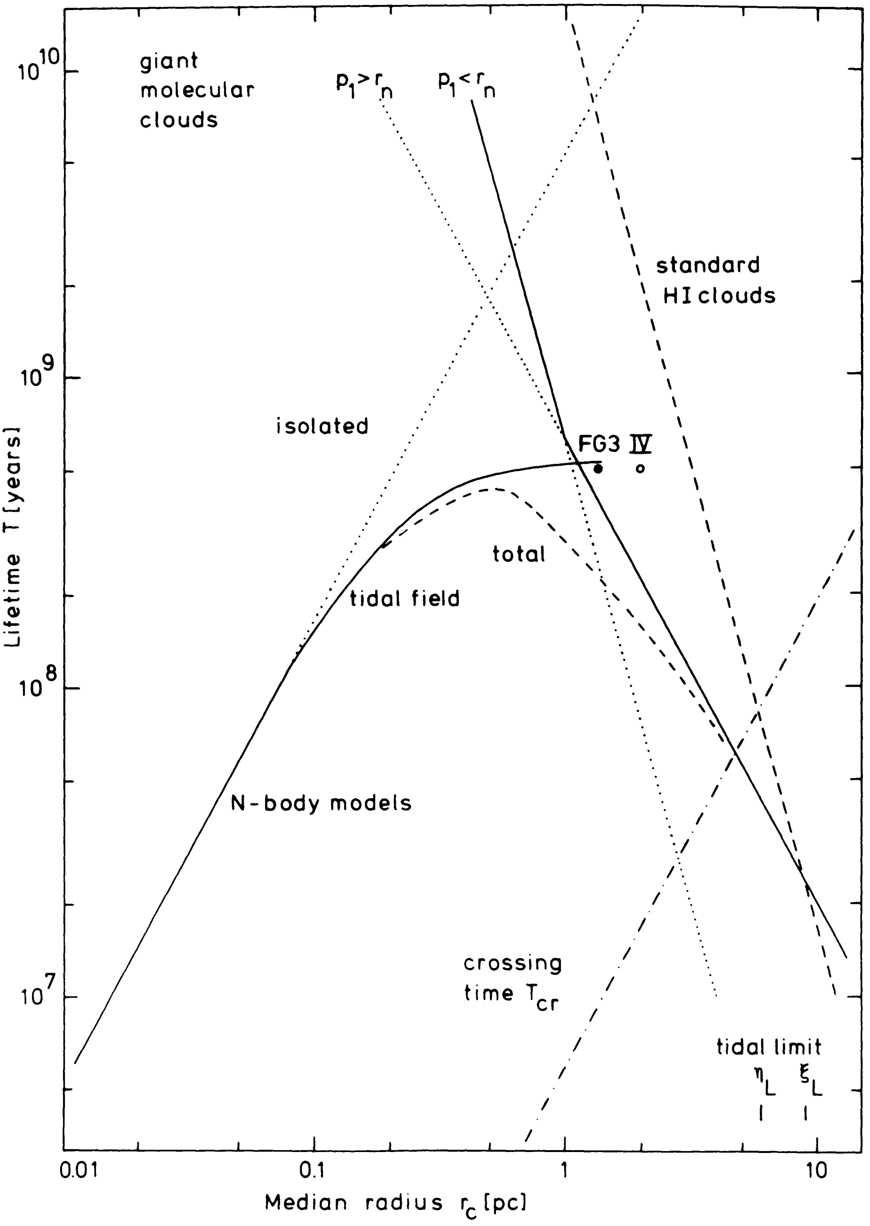

Figure 1. Total lifetime T of an open star cluster with an initial total mass of $m_c = 250\ m_\odot$ and N = 500 stars as a function of the median radius r_c of the cluster. Details are explained in the text.

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in Fig.1). This has now been nicely confirmed by direct N-body simulations: Terlevich (1983) found no differences in the lifetimes of cluster models with and without HI clouds for $r_c \sim 2$ pc.

If there were no GMCs or BHs, we would derive from Fig.1 for a typical open cluster with $m_c = 250\ m_\odot$ and $r_c \sim 1$ pc a predicted total lifetime of $T = 5 \cdot 10^8$ years. This is higher than the observed typical lifetime of $2 \cdot 10^8$ years. The N-body results for N = 500 stars and $m_c = 250\ m_\odot$ can be scaled to other values of N and m_c (keeping $m_c/N = 0.5\ m_\odot$ constant) by shifting the full curve in Fig.1 first in radius r_c by a factor of $(N/500)^{1/3}$ (to the right for N > 500) and then in lifetime T by a factor of (N/500) (upwards for N > 500). This scaling law (Wielen 1974) is theoretically predicted, but is also confirmed by N-body simulations ($N \leq 500$: Wielen (1974), N = 1000 : Terlevich (1983)). In order to explain the observed typical lifetime, we would require $m_c = 100\ m_\odot$ and $r_c \sim 1$ pc as typical initial values for an open cluster. The observed large spread in cluster lifetimes (10^8 to 10^{10} years) can be explained mainly by different initial masses (50 to 5000 $m_\odot$) of the clusters.

We shall now consider the lifetimes of open cluster including the effect of the passages of massive objects, using the results derived in Section 3. The disruption time of a cluster of $m_c = 250\ m_\odot$ due to passing giant molecular clouds are given by the full lines in Fig.1. The disruption time $T_{n,1}$ (Eqs.8 and 14) applies for $p_1 > r_n$, i.e. for $r_c > 1$ pc (Eq.13), while $T_{n,0}$ (Eq.10) is correct for $p_1 < r_n$ or $r_c < 1$ pc. $T_{n,0}$ decreases with r_c^{-3} (as for HI clouds), while $T_{n,1}$ falls off more slowly with $r_c^{-3/2}$. In order to derive the lifetime T_{total} due to the combined effect of GMCs and internal relaxation including the galactic tidal field, we add the corresponding escape rates,

$$T_{total}^{-1} = T_{GMC}^{-1} + T_{N\text{-body}}^{-1} \quad . \tag{20}$$

The result is indicated by the dashed curve labelled 'total' in Fig.1. Terlevich (1983) has carried out a few N-body simulations in which a single encounter of the cluster with a molecular cloud occurs. Using $p < p_1$, she found indeed a sudden disruption of the cluster due to the encounter. From these experiments, it is not possible, however, to derive directly a mean disruption time of a cluster for comparison with our theoretical results.

Using the results shown in Fig.1 after including the effect of GMCs (dashed curve), we now predict for a typical open cluster ($m_c = 250\ m_\odot$, $r_c = 1$ pc) a shorter total lifetime, namely $T \cong 3 \cdot 10^8$ years, in rough agreement with the observational value of $2 \cdot 10^8$ years. For clusters with larger median radii r_c, the average lifetime is even more strongly limited by the GMCs. The typical lifetime of open clusters is so short that they spend most of their life close to the galactic plane and mainly in the GMC layer. The decrease of the overall density ρ_{an} of GMCs with the galactocentric radius R may explain the observed increase of cluster lifetimes with increasing R (Section 2), because $T_{n,1}$ and $T_{n,0}$ are proportional to $1/\rho_{an}$. Another explanation of the R-dependence of the cluster lifetimes could be a systematic change of the typical initial cluster masses and radii with R, due to variations in the conditions for cluster formation (e.g. Jeans masses).

If one or a few encounters with GMCs are largely responsible for the disruption of an open cluster, then the stochastic occurence of such encounters produces already a wide spread in the lifetimes of individual clusters with the same initial values of m_c and r_c. The existence of very old open clusters can be explained by a combination of two effects: (1) a high initial mass m_c (otherwise the cluster dissolves too rapidly by internal relaxation even without GMCs), and (2) older clusters have been accelerated by the irregular part of the galactic gravitational field (Wielen 1977) and spent only a small fraction of their life inside the GMC layer, thereby increasing the mean T_n due to GMCs drastically.

Encounters with massive black holes of the galactic corona do not affect a typical open cluster, because the time scale $T_{n,1}$ (Eq.18) is much longer ($\sim 2\cdot 10^9$ years) than the typical lifetime of a cluster with $m_c = 250\ m_\odot$ and $r_c = 1$ pc. The existence of the postulated massive black holes would, however, limit the lifetime of old open clusters severely. In order to explain the survival of an open cluster over $5\cdot 10^9$ years, we would, on the average, require an initial mass of $m_c = 16000\ m_\odot$ for $r_c = 2$ pc ($\sim$ present median radius of M67 and NGC188) and of $m_c = 5000\ m_\odot$ for $r_c = 1$ pc. In deriving the numbers, we have added the escape rates (1) due to passing black holes and (2) due to internal relaxation and galactic tidal field, using the scaling law for reaching higher values of N as described earlier. Such high values for the initial masses of open clusters are rare today. They may have been more frequent in the past, however. Furthermore, due to the stochasticity of encounters of clusters with black holes, some of the old clusters may have avoided, by chance, efficient encounters with black holes up to now. Because very old open clusters are extremely rare, all these explanations seem to be reasonable. Therefore, the existence of massive coronal black holes cannot be ruled out from the point of view of open cluster dynamics. The black holes may even help to explain the scarcity of very old open clusters.

If an open cluster is suddenly disrupted by a single encounter with a massive object, most probably with a GMC, the system after the disruption will show many characteristics of a moving group. The internal velocity dispersion after the encounter will be typically of the order of 1 km/s. A moving group produced by such a sudden disruption of an old open cluster would look old from the ages of the stars, while it is actually young from a dynamical point of view, because the stars have spent most of their time in the bound cluster. In that case, a moving group composed of old stars would not be in contradiction to the existence of the irregular gravitational field in the Galaxy deduced from the age-velocity relation of nearby disk stars (Wielen 1977).

We conclude that encounters of open clusters with giant molecular clouds can probably help to understand better the dynamics, especially the lifetimes, of open clusters.

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DISCUSSION

TREMAINE: To estimate cluster disruption times one can replace the cluster by a hypothetical binary star with the same mass and rms velocity, and then use existing formulae for the half-life of binary stars (e.g. Bahcall, Hut & Tremaine, submitted to Ap.J.Lett.).

FALL: If open clusters are disrupted explosively by single encounters with giant molecular clouds, then one might expect, by analogy with a Poisson process, that the distribution of cluster ages should decline exponentially at large ages. It appears from your earlier work, however, that the distribution declines as a power of age. Are these results consistent, or is the expected distribution modified significantly by the finite velocity dispersion of the clouds and other factors?

WIELEN: If all the open clusters would have the same initial values for the total mass and the median radius, you would indeed expect, in a first approximation, an exponential decline of the age distribution for the case that close encounters with massive objects are the most important source of cluster disruption. In reality, you have a wide spread in initial cluster masses and radii. This produces already a more complex age distribution.

GRINDLAY: May I comment simply that the importance of giant molecular clouds (GMCs) for cluster disruption as you have discussed, may also be very important for globular clusters as I discussed in my talk on Tuesday. Globulars with the unfortunate initial conditions of having prograde orbits with inclinations near the plane (within $\sim \pm 10^{\circ}$) and apogalacticon distances $R \sim 4 - 6$ kpc will be disrupted within a few orbital periods by the GMC ring, if it exists, between 4-6 kpc. These disruptive encounters may also give rise to the high velocity moving groups of halo-type stars (e.g. Groombridge 1830, as discussed by Oort in his 1965 paper in the Stars and Stellar Systems Vol. V) should these also prove to be real groups. In this way yet another parallel may be drawn with the processes you discussed for open clusters.

SEMENZATO: You have an idea of the order of magnitude of the velocities of the stars of the cluster after it gets disrupted by a massive cloud. If they are high enough the disruption of the clusters might be one of the mechanisms responsible for ejecting stars out of the galactic plane and account for the early type high velocity stars which are observed at high galactic latitudes.

WIELEN: The final velocities of stars after the disruption of an open cluster by even a close encounter with a giant molecular cloud are insufficient for ejecting stars out of the galactic disk. The internal velocity dispersion of the disrupted system is typically 1 km/s, while the change in the total space velocity can reach about 20 km/s.

MATHIEU: You have discussed the effect of encounters with giant molecular clouds. It seems fairly certain that open star clusters also form in GMCs, and in the cases of NGC 2244 and NGC 2264, for example, its parent GMC is not entirely disrupted by the massive stars in its cluster. What is the dynamical effect of the parent cloud on the young cluster?

WIELEN: The dynamical effects of the parent cloud on an open cluster are difficult to predict theoretically, depending on many highly uncertain input data. From observations it is clear that (at least some) open clusters survive this period, since most of the clusters older than a few 10^7 years are found to be not anymore connected with molecular clouds.

TOOMRE: Please explain again what you have against those hypothetical massive black holes from the halo blasting apart the open clusters. You seem to say that the "hits" from 10^6 $m_\odot$ objects would be far too rare to do their needed job in 10^8 years - even though they would engage in some real overkill if they did happen to come close. But what about cutting up those very massive objects into, say, 100 black holes of 10^4 $m_\odot$ apiece. Wouldn't they thus suffice for this task?

WIELEN: I have nothing against those black holes. A higher number of less massive black holes would have roughly the same effect on the dissolution of open clusters. I used 10^6 $m_\odot$ for the mass of a black hole in the galactic corona, because a value like this was proposed by Lacey, Ostriker and Schmidt for explaining the observed heating of the galactic stellar disk.

KING: In small-N clusters about half the escapers are relatively high-velocity ones, from a single close encounter. Won't those stars avoid being retained in the corona?

WIELEN: According to my numerical experiments, even escapers with positive energies are often retained for a few galactic rotation periods, e.g. for $5 \cdot 10^8$ or 10^9 years, if no external forces help to remove them rapidly from the cluster vicinity.

LARSON: I didn't understand your remark that the equality of the scale heights of old disk stars and open clusters of the same age is consistent with acceleration of the stars by 10^6 $m_\odot$ black holes. In this picture the older field stars have larger scale heights because of acceleration, but the larger scale heights of old open clusters can't be explained this way because, as you stated earlier, an encounter between a clusters and a 10^6 $m_\odot$ black hole would destroy the cluster, so you would just end up with fewer clusters but not with a larger scale height for the surviving clusters.

WIELEN: Clusters are disrupted by the <u>tidal</u> field of passing objects, while the center-of-mass of a cluster is accelerated by the <u>total</u> force provided by the objects. Due to the much stronger decrease of the effect of the tidal field with increasing impact parameter, the more frequent <u>distant</u> encounters accelerate all the clusters, while only some of the clusters are destroyed by the rare <u>close</u> encounters.

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