DISOLUTION OF STAR CLUSTERS IN GALAXIES

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ABSTRACT

We present a procedure which allows to predict the dissolution times of star clusters in a simple way. The dissolution time of a cluster depends mainly on its total mass, its median radius and its galactic environment (galactic tidal field and passing massive objects). As an example, we discuss the lifetimes of LMC clusters. Finally, we show that massive black holes, which have been proposed as the major constituent of the dark coronae of galaxies, are very effective in destroying globular clusters.

1. INTRODUCTION

Star clusters in galaxies provide often more detailed information than individual stars: Clusters are usually brighter, the sample of clusters is relatively more complete, and, most importantly, individual ages of clusters are usually of higher accuracy than those of single stars, and the ages of observable clusters cover the whole range between the youngest and oldest objects in galaxies. Due to internal or external dynamical effects, star clusters often dissolve during a period shorter than the Hubble time. The dynamical dissolution of clusters can therefore strongly determine the distribution of presently observable properties of clusters. It is then more difficult to deduce the distribution of the original properties of clusters at birth. On the other hand, the observable age distribution of open clusters contains the most direct information on the dynamical dissolution of star clusters in a galaxy.

2. THEORETICAL PREDICTIONS FOR THE LIFETIMES OF STAR CLUSTERS

There are many mechanisms which are causing the dissolution of star clusters. The most important internal mechanism is the evaporation of stars, due to the exchange of orbital energy during

close encounters between the cluster members. The nearly stationary
tidal field of the parent galaxy can increase the evaporation rate
dramatically by lowering the limiting energy for bound stars. Internal
evolution of the individual stars causes a mass loss from the cluster,
thus weakening the binding of the cluster. Tidal shocks due to passing
objects, such as giant molecular clouds, are often a very effective
external mechanisms for the partial or complete destruction of
clusters.

2.1 Dissolution Times of Clusters Predicted from N-Body Simulations and Theoretical Extrapolations

The most direct way to determine theoretically the dissolution
times of star clusters are provided by N-body simulations. The results
of such N-body simulations have been extensively reviewed
(Aarseth 1985, Aarseth and Lecar 1975, Wielen 1974, 1975, 1985). The
most recent N-body experiments have been carried out by E.Terlevich
(1980, 1983, 1986). It is now possible to follow the dynamical
evolution of a star cluster essentially until its final dissolution.
The main limitation for N-body experiments is set by the initial
number N of stars in a cluster which can be handled on the available
computers within reasonable computing times. For star clusters, this
limit is presently of the order of N = 1000 stars. In order to
extrapolate the N-body results to higher values of N, we have to rely
on theoretical extrapolations.

We consider first the dissolution of a cluster due to the
combined effects of the internal relaxation and the stationary tidal
field of the galaxy alone. Mass loss of evolving stars is neglected,
since it does not seem to alter the results dramatically. Tidal shocks
due to passing giant molecular clouds or massive black holes are
discussed in Section 2.2.

2.1.1 Isolated Clusters

For isolated clusters, we use the theory developed by Hénon
(1960, 1969) in order to extrapolate the results of N-body simulations
to higher values of N. Hénon's theory is based on the assumption that
close encounters between cluster stars are the most important source
of escaping stars. This assumption has been nicely confirmed by the
N-body simulations, which showed that most of the escapers gain the
necessary energy indeed during close encounters with single stars or
binaries. This result is not in contradiction to another result of
N-body simulations (Aarseth, Hénon and Wielen, 1974), namely that the
overall dynamical evolution of a cluster is rather accurately
described by a Fokker-Planck equation based on the predominance of
more distant, weak encounters. It means only that the rare escape
events are not due to the otherwise dominant diffusion of stars in
phase space.

Using Hénon's theory, we predict for the evaporation time T,

$$T = -N/(dN/dt) = NT_{cr}/\phi_0 \quad . \qquad (1)$$

The crossing time T_{cr} for a Plummer model is given by

$$T_{cr} = (32/(3\pi))^{3/2}(Gm_c/r_c^3)^{-1/2} \quad , \qquad (2)$$

where m_c is the total mass of the cluster, r_c is the median radius of the cluster (containing half of m_c in projection), and G is the gravitational constant. The quantity ϕ_0 in Eq. 1 is best determined from N-body experiments. For a cluster with a realistic distribution of stellar masses, similar to Salpeter's law, we find for the number of stars which escape during one crossing time:

$$\phi_0 = 0.56 \qquad . \qquad (3)$$

Eqs. 1, 2 and 3 allow to predict the dissolution time of an isolated star cluster for any initial value of N, m_c and r_c, provided that our assumptions are also valid outside the experimentally explored range of N.

2.1.2 Tidally Limited Clusters

The theory presented in Section 2.1.1 can be extended to tidally limited clusters. The N-body experiments show that even for tidally limited clusters, close encounters produce still the overwhelming fraction of escapers. It can be shown that, to a first approximation, the number of escapers per crossing time depends on the ratio between the radius r_c and the tidal radius r_t of the cluster only. This leads to the following prediction for the dissolution time T of tidally limited clusters:

$$T = NT_{cr}/(\phi_0 f(r_c/r_t)) \quad . \qquad (4)$$

ϕ_0 is given by Eq. 3, and the function $f(r_c/r_t)$ has been derived by fitting the results of N-body simulations of tidally limited clusters (Fig. 1). The fitting curve corresponds to

$$f(r_c/r_t) = (1 + (43r_c/r_t)^3)^{1/2}. \qquad (5)$$

This expression has the desired properties: f approaches 1 for small radii r_c (isolated clusters), and T becomes independent of r_c for large radii r_c (strongly tidally limited clusters). The tidal radius r_t is given by

$$r_t = (Gm_c/(4\omega^2-\kappa^2))^{1/3} \quad , \qquad (6)$$

where the local rotational frequency ω and the local epicyclic frequency κ have to be derived from the rotation curve of the parent galaxy. If we introduce a 'tidal time' T_t,
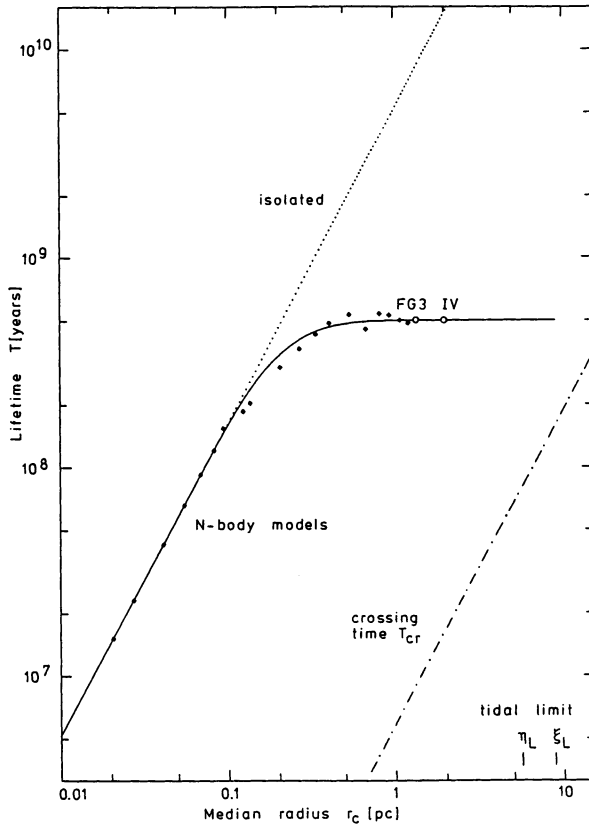
Fig. 1.   Fit of the results of N-body simulations for the dis-
           solution time T of a cluster with N = 500 stars and
m_c = 250 $m_\odot$ as a function of the median radius r_c of the clus-
ter. N-body models from Wielen (1975, full squares and FG3) and
Terlevich (1983, IV). Solid curve: T from Eqs. 4 and 5.

$$T_t = (r_t/(43r_c))^{3/2}\, T_{cr}$$

$$= (32/(3\pi \cdot 43))^{3/2}(4\omega^2 - \kappa^2)^{-1/2}$$

$$= 0.022\ (4\omega^2 - \kappa^2)^{-1/2}\ , \qquad (7)$$

then the function f can be expressed in terms of the ratio between the
crossing time T_{cr} of the cluster and the tidal time T_t,

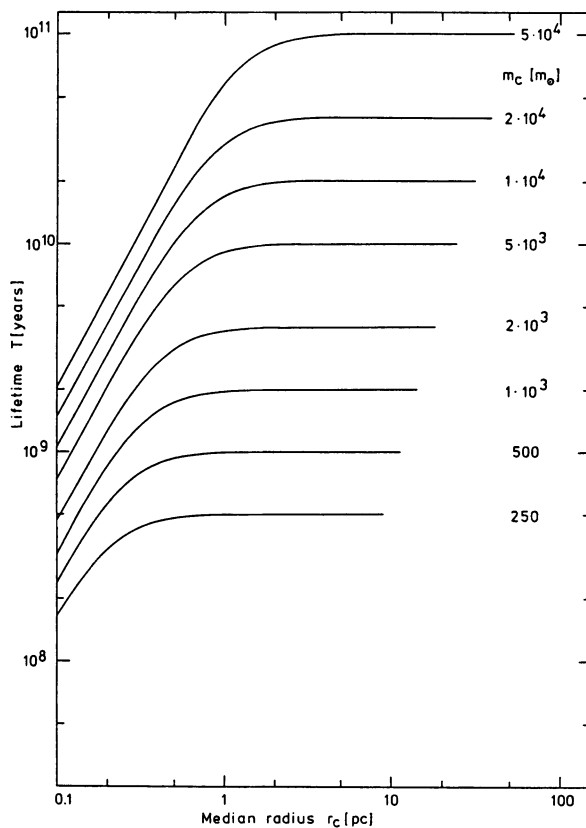$$f(r_c/r_t) = f(T_{cr}/T_t) = (1 + (T_{cr}/T_t)^2)^{1/2}\ . \qquad (8)$$

Fig. 2.   Dissolution time T of a tidally limited star cluster
           in the solar neighbourhood as a function of the medi-
an radius r_c of the cluster for various total masses m_c, based
on Eqs. 4 and 5.

Eqs. 4 and 5 or 8, together with the expression for T_{cr}, r_t, T_t and ϕ_0
= 0.56, provide now the necessary instruments for predicting the
dissolution time of a tidally limited star cluster with any value of
N, m_c, r_c and r_t.

In Fig. 2, we present results based on our procedure, for star
clusters in the solar neighbourhood with a realistic spectrum of stel-
lar masses and a mean stellar mass of m_c/N = 0.5 $m_\odot$. The dissolution
time T is plotted as a function of r_c for various values of m_c.

In the limit of large cluster radii r_c, i.e. for strongly tidally
limited clusters in which r_c is not much smaller than r_t, we get the
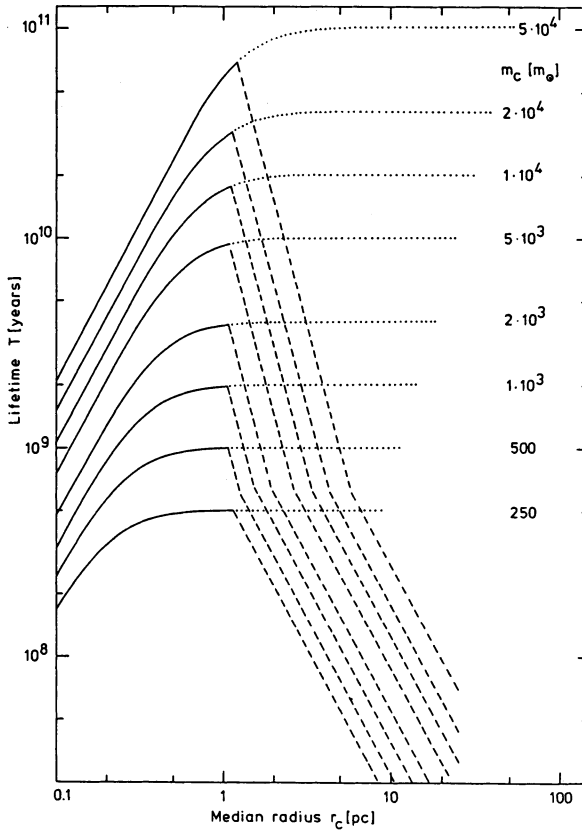following simple expression for the dissolution time:

Fig. 3.   Dissolution time T of a star cluster in the solar
           neighbourhood. The full (and dotted) curves are taken
from Fig. 2. The dashed lines give the dissolution times due to
giant molecular clouds (GMCs).

$$T_{lim} = NT_t/\phi_0 \qquad\qquad (9)$$

The dissolution time T_{lim} is independent of r_c and proportional to N,
or to m_c for a fixed value of the mean stellar mass (m_c/N). In the
solar neighbourhood, the tidal time T_t is about $0.56\cdot10^6$ years. This
leads to $T_{lim} = N\cdot10^6$ years or, for example, to $T_{lim} = 10^{10}$ years for
N = 10000 stars ($m_c = 5000\ m_\odot$ for $m_c/N = 0.5\ m_\odot$). Clusters with N much
higher than 10^4 do not dissolve in a Hubble time, if we consider only
internal relaxation and a stationary galactic tidal field. Hence our
extrapolation from N $\leq$ 1000, covered by N-body simulations, to the
highest values of real interest, N $\sim 10^4$, is by one order of magnitude
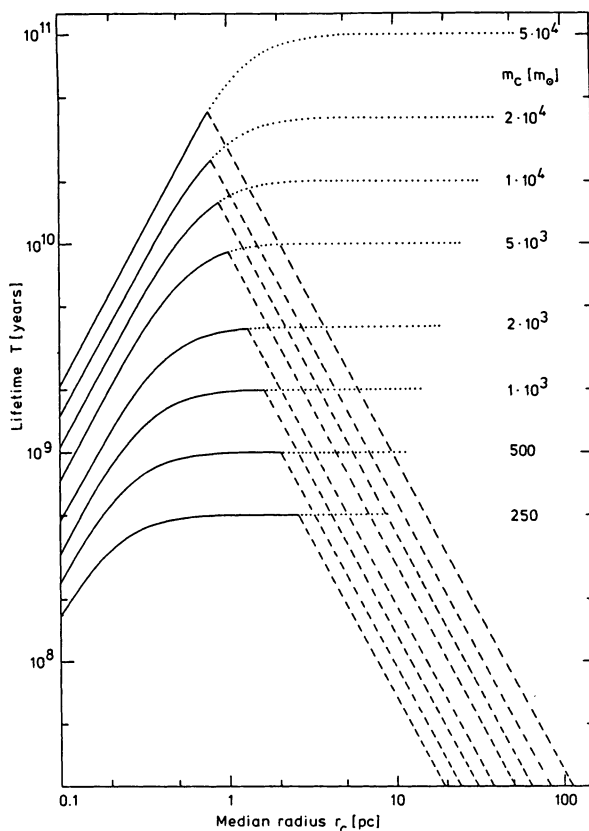only. I would consider that as not too risky.

Fig. 4.   Dissolution time T of a star cluster in the solar
           neighbourhood. The full (and dotted) curves are taken
from Fig. 2. The dashed lines give the dissolution times due to
massive black holes (MBHs).

2.2 Dissolution Times of Clusters due to Passing Massive Objects

Star clusters can also be dissolved by passing massive objects.
Important effects can be caused especially by giant molecular clouds
(GMC) or by massive black holes (MBH). For a detailed discussion we
refer to an earlier paper (Wielen, 1985). For completeness we repeat
here the final results for the dissolution times T_n of star clusters
due to passing massive objects. A massive object is characterized by
its mass m_n and its radius r_n; ν_n is the number density of the massive
objects in the neighbourhood of the cluster; $\rho_{an} = m_n\nu_n$ is the overall
mass density of the objects; V is the relative velocity between the
object and the cluster; and αr_c is the effective radius of the cluster

for tidal shocks ($\alpha = 1$ may be used as a first guess).

Two different cases for the dissolution of clusters by passing objects occur. They are characterized by the relative size of the limiting impact parameter p_0,

$$p_0 = \max(r_n, r_c) \ , \tag{10}$$

with respect to the critical impact parameter p_1,

$$p_1 = 4(\alpha/3)^{1/2}(G/\pi)^{1/4}m_n^{1/2}V^{-1/2}(m_c/r_c^3)^{-1/4} \ . \tag{11}$$

In the case of $p_1 > p_0$, the cluster can be destroyed completely by a single encounter, if the massive object passes with an impact parameter $p < p_1$. In this case ($p_1 > p_0$), the mean dissolution time $T_{n,1}$ of a cluster is given by

$$T_{n,1} = (3/(32\alpha))\pi^{-1/2}(Gm_c/r_c^3)^{1/2}/(G\rho_{an}) \ . \tag{12}$$

It is remarkable that $T_{n,1}$ depends only on the overall mass density ρ_{an}, but not on the individual values of m_c, r_c or V of the passing objects.

In the case $p_0 > p_1$, a number of successive encounters are necessary for disrupting the cluster. The resulting dissolution time $T_{n,0}$ of a cluster is given by

$$T_{n,0} = (9/(512\alpha^2)) \ G^{-1}m_n^{-1}\rho_{an}^{-1} \ V \ m_c r_c^{-3} p_0^2 \ , \tag{13}$$

where p_0 is either r_n or r_c according to Eq. 10.

Both expressions, $T_{n,0}$ and $T_{n,1}$, are only valid if the encounter between the cluster and the object is impulsive (Spitzer, 1958), i.e. if $p/V < T_{cr}$. This is essentially fulfilled if

$$\max(p_0, p_1) < V \ T_{cr} \ . \tag{14}$$

In order to calculate T_n for a given cluster, one has firstly to determine p_0 and p_1 from Eqs. 10 and 11, secondly to check the impulsive approximation according to Eq. 14, and then finally to compute T_n either from Eq. 12 ($T_{n,1}$ for $p_1 > p_0$) or from Eq. 13 ($T_{n,0}$ for $p_0 > p_1$). The resulting dissolution time T_n neglects the effect of the galactic tidal field, which would tend to reduce the values for T_n, because it again lowers the limiting energy for bound stars.

In Figs. 3 and 4, we have plotted the dissolution time T_n of clusters as dashed lines, either due to giant molecular clouds (Fig. 3) or massive black holes (Fig. 4). The parameters used are $m_n = 5 \cdot 10^5$ $m_\odot$, $r_n = 25$ pc, $\rho_{an} = 0.02$ $m_\odot/pc^3$ and $V = 10$ km/s for GMCs, and $m_n = 3 \cdot 10^6$ $m_\odot$, $r_n = 0$, $\rho_{an} = 0.006$ $m_\odot/pc^3$ and $V = 250$ km/s for MBHs (see Wielen, 1985).
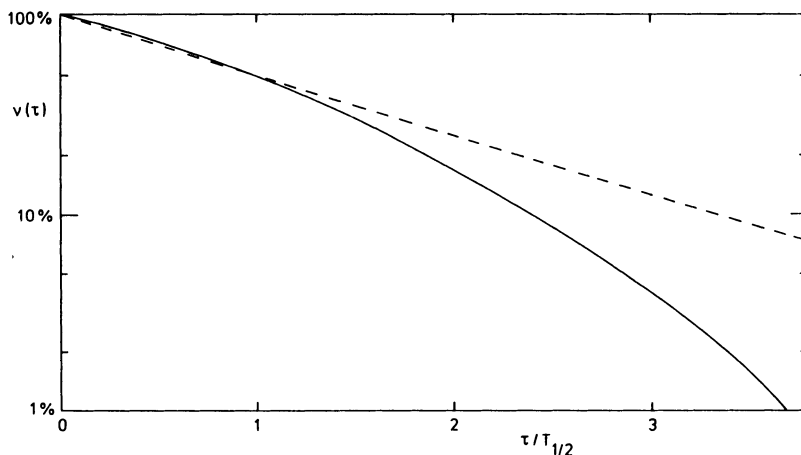
Fig. 5.   Survival rate ν of clusters with the same initial
           values of N, m_c and r_c as a function of the age τ
(scaled by the median value $T_{1/2}$ of the dissolution times).
Disruption of clusters due to GMCs (or MBHs) in a case with
$p_1 \gg p_0$. Evaporation due to internal relaxation neglected here.

If a type of clusters may be destroyed completely by a single
encounter with a passing object, i.e. if $p_1 > p_0$, then there is a wide
spread in the actual lifetimes of individual clusters, caused by the
stochastic occurence of such encounters. Hence the dissolution time T_n
derived above has to be interpreted as an expectation value (mean
value) for the lifetime only. Kuhrau and Wielen (unpublished) have
carried out Monte-Carlo simulations on the disruption of clusters due
to passing objects. A typical result of these studies is shown in Fig.
5. The full curve gives the survival rate $\nu(\tau)$, i.e. the percentage of
clusters which live longer than τ, for a case with $p_1 \gg p_0$. All
clusters had initially the same total mass and radius. The initial
decline of $\nu(\tau)$ is roughly exponential (dashed line), as expected for
random close encounters. For larger ages τ, the accumulating number of
distant encounters causes a steeper decline of ν.

2.3 Total Dissolution Times

In order to derive the dissolution time T_{total}, due to the
combined effect of internal relaxation and passing objects, we add the
corresponding escape rates, 1/T:

$$T_{total}^{-1} = T_{N\text{-}body}^{-1} + T_{GMC}^{-1} + T_{MBH}^{-1} \quad . \tag{15}$$

Here, $T_{N\text{-}body}$ is to be taken from Section 2.1, while T_{GMC} and T_{MBH}
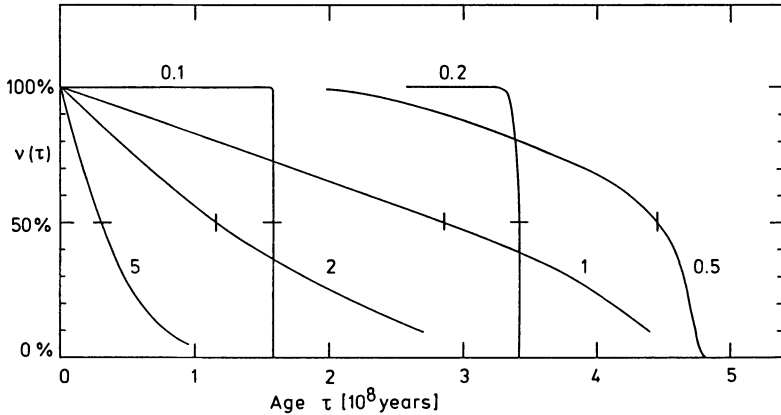have to be derived from Section 2.3. In Figs. 3 and 4, we have not

Fig. 6.   Survival rate ν of clusters with the same initial
            values of m_c = 250 $m_\odot$, N = 500 stars and various val-
ues of r_c (in pc) as a function of age τ. Dissolution of clus-
ters due to internal relaxation, galactic tidal field and GMCs.

plotted the total dissolution time, since this would have obscured the
picture. An example of a curve for the total dissolution time is shown
in Fig. 1 of Wielen (1985). At the 'crossing points', the total
dissolution time is half of T_{N-body} = T_{GMC}, while for small (large)
radii, T_{total} approaches T_{N-body} (T_{GMC}).

As discussed in Section 2.2, close encounters with passing
massive objects produce a wide distribution of actual lifetimes, even
for clusters with the same initial values of m_c, r_c and r_t. To the
contrary, the internal relaxation leads to rather well-defined
dissolution times. The width of the distribution function of total
lifetimes depends therefore on the relative importance of internal
relaxation and close encounters with GMCs or MBHs. An example for the
survival rate ν(τ) of clusters with m_c = 250 $m_\odot$, N = 500 stars and
various values of r_c is shown in Fig. 6 (Kuhrau and Wielen,
unpublished).

3.   STAR CLUSTERS IN THE LARGE MAGELLANIC CLOUD (LMC)

We will now apply the procedure presented in Section 2 to star
clusters in the LMC. For deriving the tidal time T_t (Eq.7) as a
function of the distance R from the center of the LMC, we need the run
of $4\omega^2-\kappa^2$ based on the rotation curve of the LMC. We use the results
of Elson and Freemann (1986). The tidal time in the LMC increases from
$0.4\cdot10^6$ years at R ⌁ 1° to $1.1\cdot10^6$ years at R ⌁ 6°. At R ⌁ 3°, the
tidal time in the LMC is just about equal to the value in the solar
neighbourhood, $0.6\cdot10^6$ years, so that Fig. 2 can be directly used for
LMC clusters at R ⌁ 3°.

If we consider only the dissolution of clusters due to internal relaxation combined with the LMC tidal field, then all clusters with median radii r_c larger than about 1 pc and with total masses m_c above 7500 $m_\odot$ at R $\sim$ 3°, above 9000 $m_\odot$ at R $\sim$ 1°, and above 4000 $m_\odot$ at R $\sim$ 6° should have survived over 15·10^9 years. Clusters with smaller total masses would live shorter, in direct proportion to their value of m_c.

The overall density of molecular gas in the LMC is still rather uncertain (Israel, 1984, Cohen et al., 1984). Hence it is essentially impossible to estimate at present the effect of molecular clouds on LMC clusters. Since the molecular gas seems to be less abundant in the LMC than in our Galaxy, its effect on LMC clusters is correspondingly smaller than for galactic clusters. For LMC clusters with large median radii, however, large molecular clouds may still be the dominant source of cluster dissolution.

Elson and Fall (1985) have derived the age distribution for rich star clusters in the LMC from observational data. They find a decrease of the number of clusters with increasing age similar to that of open clusters in our Galaxy (Wielen, 1971) for ages up to 3·10^8 years, and a flatter tail for older LMC clusters. The indicated short median dissolution time of about 2·10^8 years for these rich LMC clusters with $m_c > 10^3$ $m_\odot$ would require strong effects from passing massive objects such as giant molecular clouds. However, due to the various assumptions which enter into the derivation of the 'observed' age distribution of LMC clusters, this conclusion is quite uncertain at present. Mateo (1986) has presented an age distribution for less massive LMC clusters which differs strongly from the results of Elson and Fall. Mateo's data indicate a median dissolution time of about 3·10^9 years for a constant formation rate. The discrepancy may be, at least partially, due to the different locations of the cluster samples (typically R $\sim$ 2° for Elson and Fall, and R $\sim$ 6° for Mateo). Mateo's results can be explained, if the effect of GMCs are negligible in the LMC at R $\sim$ 6°. For this distance, we would then predict a dissolution time of 2·10^9 years for a cluster with m_c = 500 $m_\odot$ and $r_c > 1$ pc.

4. THE EFFECT OF MASSIVE BLACK HOLES ON GLOBULAR CLUSTERS

Massive black holes (MBHs) have been proposed by Lacey and Ostriker (1985) and Ipser and Semenzato (1985) as the major constituents of dark galactic coronae. These MBHs would nicely explain the increase in the velocity dispersion of disk stars as a function of age as derived by Wielen (1977). If the MBHs really exist, they would be extremely efficient in dissolving globular clusters.

In Table 1, we give the dissolution times for globular clusters of various total masses and median radii, at the solar distance from the galactic center, due to MBHs. For the MBHs, we use the same

Table I
Disruption time T_n (in 10^9 years) for
globular clusters due to massive black holes

mass m_c (in $m_\odot$) of the cluster	median radius r_c (in pc) of the cluster				
	1	2	5	10	20
$2 \cdot 10^6$	**188**	69	28	14	6.9
$1 \cdot 10^6$	**133**	**47**	14	6.9	3.5
$5 \cdot 10^5$	**94**	**33**	**8.4**	3.5	1.7
$2 \cdot 10^5$	**59**	**21**	**5.3**	**1.9**	0.7
$1 \cdot 10^5$	**42**	**15**	**3.8**	**1.3**	**0.5**
$5 \cdot 10^4$	**30**	**11**	**2.7**	**0.9**	**0.3**
$2 \cdot 10^4$	**19**	**6.6**	**1.7**	**0.6**	**0.2**
$1 \cdot 10^4$	**13**	**4.7**	**1.2**	**0.4**	**0.1**

bold face : $T_{n,1}$ ($p_1 > r_c$)
normal   : $T_{n,0}$ ($p_1 < r_c$)

Table II
Survival rate ν (in %) for globular
clusters of age $\tau = 15 \cdot 10^9$ years in
the presence of massive black holes

mass m_c (in $m_\odot$) of the cluster	median radius r_c (in pc) of the cluster				
	1	2	5	10	20
$2 \cdot 10^6$	96	89	(71)	((47))	((19))
$1 \cdot 10^6$	94	83	47	(19)	((1))
$5 \cdot 10^5$	92	75	24	1	0
$2 \cdot 10^5$	87	62	8	0	0
$1 \cdot 10^5$	80	50	1	0	0
$5 \cdot 10^4$	73	36	0	0	0
$2 \cdot 10^4$	59	15	0	0	0
$1 \cdot 10^4$	44	5	0	0	0

parameters as in Section 2.2, namely $m_n = 3 \cdot 10^6$ $m_\odot$ and
$\rho_{an} = 0.006$ $m_\odot/pc^3$. For the relative velocity between MBHs and
globular clusters, we assume $V = 2^{1/2} \cdot 220$ km/s = 311 km/s. A typical
globular cluster with $m_c = 2 \cdot 10^5$ $m_\odot$ and $r_c = 5$ pc has a mean lifetime
T_n of only $5 \cdot 10^9$ years, i.e. about one third of the Hubble time.
Clusters with larger radii or smaller masses are even more vulnerable
by MBHs.

The dissolution times of globular clusters are inversely
proportional to the overall mass density ρ_{an} of the MBHs in the
corona. Therefore, the dissolution time T_n of a globular cluster
depends strongly on its (mean) galactocentric distance R, T_n being
shorter in the inner parts of the Galaxy and longer in the outer
regions. The decrease of ρ_{an} at larger distances follows the relation
$\rho_{an} \propto R^{-2}$ for a flat rotation curve. This would imply $T_n \propto R^2$. The
increase of ρ_{an} towards the galactic center is not well-known
quantitatively. According to Lacey and Ostriker (1985), the central
density ρ_{an} of MBHs may be higher than their local density by a factor
of 2 or more. The dissolution times of globular clusters due to MBHs
in the central region of the Galaxy are then correspondingly shorter
than the values given in Table I.

It may seem at first that dissolution times significantly shorter
than the Hubble time would be a strong argument against the existence
of MBHs, since the observed globular clusters have ages of about
$15 \cdot 10^9$ years. One should remember, however, that the disruption of
globular clusters by MBHs is a highly stochastic process, leading to a
wide spread in the lifetimes of clusters (Section 2.2). We have
therefore derived the percentage ν of globular clusters which survive
over a period of $15 \cdot 10^9$ years as a function of m_c and r_c. The survival
rates ν presented in Table 2 are based on the dissolution times given
in Table 1, and on a relative survival function similar to that shown
in Fig. 5. From Table 2, we see, for example, that 8 % of globular
clusters with an initial total mass of $m_c = 2 \cdot 10^5$ $m_\odot$ and a median
radius of $r_c = 5$ pc would survive over $15 \cdot 10^9$ years at the solar
distance R_o. This means that in order to explain the presently
observed number of such clusters, the initial population of clusters
of that type had to be larger than now by a factor of 1/0.08 = 12.5.
The general conclusion is that if the proposed massive black holes do
exist, the initial number of globular clusters was much higher than
now. It may even be that all halo field stars were formerly members of
now dissolved clusters.

A possible argument against the existence of MBHs would come from
a universal distribution function for the total luminosities of
globular clusters. It is clear from Tables I and II that MBHs would
strongly modify any initial distribution of total masses of globular
clusters and would probably even determine the location of the peak in
the luminosity function of globular clusters and the shape of this
function for low cluster luminosities. In galaxies like our one, the
dependence of T_n on R would produce a strong radial change in the

luminosity function, which does not seem to be observed. From galaxy to galaxy, one would expect a variation in the location of the maximum of the luminosity function of globular clusters, if there is not a kind of universal coupling between the distribution of globular clusters and the density distribution of MBHs in dark coronae of galaxies.

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Note added in proof: Elson and Freeman 1986 should be replaced by Elson, R. A. W., Fall, S. M. and Freeman, K. C. 1987, preprint.

DISCUSSION

INAGAKI: Does the disruption time become significantly shorter if you take into account the post-collapse expansion?

WIELEN: The N-body simulations of cluster dissolution cover in many cases the 'post-collapse' phase.   There is no indication for a significant change of the escape rate with time.   In the case of an encounter between a cluster and a passing massive object, the actual radius of the cluster at that time determines the fate of the cluster. This effective radius of the cluster may be, of course, affected by post-collapse expansion.

SCHOMMER: Two comments on your LMC comparison.   It would be relatively easy for someone to measure tidal radii, using CCD frames from small telescopes, of many LMC clusters.   Secondly, while I find the Elson and Fall analysis impressive, I am worried about their sample completeness. In particular, they need to correct the Van den Bergh compilation by counting from Hodge Atlas Plates, by factors of 4-5 for the faintest, oldest clusters, precisely those with $t > 10^9$ yrs, which lie away from your galactic line; these correction factors may vary from region to region, which could easily bring their age distribution up to that of Mateo.

COHEN: What effect do those proposed massive black holes have on the velocity dispersion of halo stars?

WIELEN: The relative increase in the velocity dispersion of halo stars, due to the proposed massive black holes, is rather small at the solar distance.   To get a first guess, one may just add quadratically the velocity dispersion of the oldest disk stars (~ 80 km/s) to the total velocity dispersion of halo stars (say 270 km/s).   This leads to about 280 km/s, or an increase by 4%.   In the inner part of the Galaxy, the increase in the velocity dispersion of halo stars by black holes is larger, but probably still not overwhelming, depending mainly on the assumed increase in the number density of the black holes towards the galactic center.

BHATIA: What is the effect of the globular/open clusters on the molecular clouds?

WIELEN: The passing clusters will increase the internal energy of the molecular clouds by tidal heating.   Since most open clusters have much smaller masses than giant molecular clouds, the effect is probably small in most cases.

INNANEN: There is a relative absence of globular clusters between R ~ 20 kpc and R ~ 70 kpc.   Could the proposed black holes selectively destroy clusters that once might have been there?

WIELEN: Probably not. The disruption time for a given type of globular clusters is mainly proportional to the overall density of the black holes. This density is probably decreasing monotonically with increasing galactocentric distance R. There is also no indication that the initial masses or radii of globular clusters vary in a dramatical way with R.

KING: Can you estimate how much your results would change if it turned out that in the richer clusters the dominant escapes are due to Fokker-Planck diffusion?

WIELEN: In the case of a Fokker-Planck diffusion, the evaporation time of a cluster would increase only as $N/\log_{10}(0.4N)$ instead of N. For example, extrapolating from N = 500 to 5000 stars, the resulting evaporation time for N = 5000 would have to be decreased by a factor of $\log(0.4 \times 500)/\log(0.4 \times 5000) = 0.7$ relative to my results based on escapers by close encounters. Even for a globular cluster with $N = 10^6$ stars, the reduction factor would be only about 0.4.