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Globular Clusters and Molecular Clouds: Tidal Shocks

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Abstract—It is shown that a single encounter with a molecular cloud can result in direct tidal disruption of open clusters, but not of globular clusters. However, multiple tidal shocks produced by such encounters can also destroy globular clusters. An extended version of impulse approximation for calculating the change of the cluster energy during its evolution is developed. The tidal-shock efficiency for tidally limited clusters is shown to depend primarily on the cluster concentration. Calculations performed for our Galaxy suggest possible disruption of globular clusters with perigalacticon distances, $R_p < 0.8$ kpc, and $3 < R_p < 10$ kpc, moving in low-eccentricity, low-inclination orbits. Observational data confirm the deficit of clusters in these regions.

INTRODUCTION

Two populations of objects with extremely high individual masses are known in the Galaxy: globular clusters and giant molecular clouds (GMC). The globular clusters and GMCs have similar average and maximum masses ($\sim 10^5 M_\odot$ and $5 \times 10^6 M_\odot$, respectively) and about the same typical sizes (~10 pc). However, these two populations differ essentially in other parameters. Molecular clouds are extremely young Population-I objects, which are concentrated in the thin disk of the Galaxy – mainly in the 3–7 kpc region from its center – and which move in circular orbits. The globular clusters belong to extreme Population II, fill the bulge and halo up to 100 kpc from the Galactic center, and move in various orbits.

How strong is the interaction between these two types of massive objects? Should it be taken into account on cosmological time scales? Can it explain any of the observed features of the two populations? To analyze these problems, here we concentrate on the disruptive effect of GMCs on globular clusters. The point is that GMCs are a continually regenerated population consisting of short-lived objects. Therefore, we consider the effect of star clusters on the evolution of GMCs to be of little interest. In contrast, even weak disruptive influence that GMCs exert on globular clusters on a cosmological time scale could have left a detectable imprint on this small relict population in our Galaxy.

The gravitational field is known to have a disruptive effect on star clusters (Spitzer 1987). A steady (in the cluster reference frame) external field limits the cluster size, and a time-dependent field "heats" the cluster and can result in its disruption. The gradients of the regular Galactic field change most greatly near the Galactic core and in the Galactic disk. The evolution of globular clusters under the action of tidal gravitational shocks has been a subject of numerous investigations (Ostriker *et al.* 1972; Keenan and Innanen 1975; Surdin 1979, 1992, 1993), which showed the effect to be quite significant.

The effect of the irregular component of the Galactic field on the evolution of star clusters was also investigated. However, these studies involved only open clusters, which populate the Galactic disk and corotate with it. Spitzer (1958) used impulse approximation to analyze for the first time the disruption of star clusters by massive objects. The expected effect turned out to be rather weak because of moderate masses of HI clouds, which were at the time the only massive objects known. However, the discovery in the Galaxy of much more massive GMCs reanimated the interest in the dynamic interaction of clouds and star clusters (Spitzer and Chevalier 1973; Wielen 1985). This interaction proved to play an essential and in some cases a decisive role in the evolution of open clusters: the time scale of tidal disruption for disk clusters in the solar neighborhood varies from 10^8 to 10^9 years (Wielen 1991; Wielen and Fuchs 1988).

Only approximate estimates have been made for the effect of GMCs on globular clusters. These estimates led Spitzer (1987) to conclude that, in contrast to open clusters, "for globular clusters, with their higher internal density and higher velocity relative to the gas clouds, disruption by such clouds appears unimportant." At about the same time, Surdin (1986) found the distribution of Galactocentric distances of GMCs to anticorrelate with that of perigalacticon distances of the globular-cluster orbits. We now return once more to this problem in order to test whether Spitzer's statement is theoretically justifiable. Below I show Spitzer's conclusion to be correct for most of the presently existing globular clusters. However, clusters moving in low-inclination orbits in the direction of Galactic rotation are disrupted appreciably as a result of their interaction with GMCs. Furthermore, the evolution of the GMC

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system itself, in particular, its larger population in the past, if taken into account, makes such interaction an important factor in the evolution of the initial globular-cluster system.

Note that GMCs were not the only possible inhomogeneity sources in the Galactic gravitational field that were considered. Some of the authors invoked hypothetical massive black holes, which were earlier used to account for the dark mass in the Galactic halo. If these black holes are assumed to contain the entire dark mass in the Galaxy, they could account for a substantial destruction of the population of globular clusters (Wielen and Fuchs 1990). However, this assumption does not agree with low X-ray luminosity of the Galaxy (Fabbiano 1989), and therefore must be rejected. In the following, we ignore massive black holes and restrict the analysis to the dynamical role of GMCs.

TIDAL INTERACTION AT SLOW ENCOUNTERS

In principle, a single encounter of a star cluster of density ρ with a GMC of density ρ_{GMC} can result in complete disruption of the former. For this to occur, first, the following classical condition for tidal instability (King 1962) must be satisfied:

$$\rho < 3\rho_{GMC}. \quad (1)$$

This condition follows from the requirement that the tidal acceleration exceeds the proper gravitational acceleration of a star toward the cluster center. The second condition requires the relative encounter velocity, V, of the cloud and the cluster to be small enough not to exceed substantially the escape velocity from the GMC at the tidal-stability boundary of the cluster. This condition follows from the fact that the internal energy (or the shape) of the cluster must change substantially during the time required to cross the instability domain. It can be written as follows:

$$V < v_{GMC}\left(\frac{\rho}{\rho_{GMC}}\right)^{1/6}, \quad (2)$$

where $v_{GMC} \equiv (GM_{GMC}/R_{GMC})^{1/2}$ is the typical velocity in the cloud. Theuns (1992) confirmed the above criteria for tidal disruption by numerically simulating a head-on collision of a star cluster with a GMC.

We now consider the density ratio of globular clusters and GMCs. In a regular galactic gravitational field, the maximum size of a star cluster is limited by its tidal radius:

$$r_t = R_p\left[\frac{M}{\beta M_G(R_p)}\right]^{1/3}, \quad (3)$$

where M is the mass of the cluster; $M_G(R_p)$ is the mass of the Galaxy within the perigalacticon distance of the cluster orbit (R_p), and the coefficient β depends on the distribution of this mass. For the Galaxy model with the mass distribution in the form of a singular isothermal sphere with constant circular velocity, V_c, we have

$$M_G(R_p) = \frac{R_p V_c^2}{G}. \quad (4)$$

In this case $\beta \approx 3$ (Seitzer 1985). Since for almost all of the globular clusters, the relaxation time scale, t_{rh}, is substantially shorter than the age, it appears natural to assume that the physical radius of the cluster is close to r_t. The median radius of the cluster (r_h) and the median projected radius (r_{hP}) are related to r_t through the core radius, r_c, or the King concentration parameter $C \equiv \log(r_t/r_c)$ (Fall and Rees 1977; Spitzer 1987):

$$r_h \simeq 1.4 r_{hP} \simeq 0.70\sqrt{r_c r_t} = 0.70 r_t \times 10^{-C/2}. \quad (5)$$

It follows from (3)–(5) that the average density of the cluster within r_t is

$$\rho_t = 8\left(\frac{V_c}{220\ \mathrm{km\ s^{-1}}}\right)^2\left(\frac{R_p}{1\ \mathrm{kpc}}\right)^{-2} M_\odot\ \mathrm{pc}^{-3}. \quad (6)$$

Since for most of the clusters, the concentration parameter is in the range $1 \le C \le 2$, the average density within r_h in order of magnitude is

$$\rho_h \sim 2\times10^2\left(\frac{V_c}{220\ \mathrm{km\ s^{-1}}}\right)^2\left(\frac{R_p}{1\ \mathrm{kpc}}\right)^{-2} M_\odot\ \mathrm{pc}^{-3}. \quad (7)$$

On the other hand, the average density of individual GMCs that populate the molecular ring of the Galactic disk ($3 \le R \le 10$ kpc) is related to their mass as follows:

$$\rho_{GMC} = 5\left(\frac{M_{GMC}}{10^5 M_\odot}\right)^{-1/2} M_\odot\ \mathrm{pc}^{-3}. \quad (8)$$

For the commonly accepted GMC mass range (10^4–$10^6 M_\odot$) this formula yields $\rho_{GMC} \sim 2$–$16\ M_\odot\ \mathrm{pc}^{-3}$.

It thus follows that condition (1) for ρ_t and ρ_h is satisfied in the regions $R > (0.4$–$1)$ kpc and $R > (2$–$6)$ kpc, respectively. Hence, within the molecular ring of the Galaxy a close encounter of a tidally limited star cluster with a GMC results in substantial disruption of the former, provided that the encounter in question satisfies the condition (2). As is evident from (8), the typical velocity in the GMC is

$$v_{GMC} = 5\left(\frac{M_{GMC}}{10^5 M_\odot}\right)^{1/4} \mathrm{km\ s^{-1}}, \quad (9)$$

i.e., it depends only slightly on the mass of the cloud and is confined within a narrow range from 3 to 9 km $\mathrm{s^{-1}}$. The dispersion of spatial residual velocities (relative to the total Galactic rotation) is $\approx$8 km $\mathrm{s^{-1}}$ for GMCs and about 16 km $\mathrm{s^{-1}}$ for young open clusters (Glushkova *et al.* 1997). Therefore, (2) is evidently of little importance for open clusters: in many cases the very first encounter of a cluster with a GMC must result in a complete disruption of the former. In any event, several such successive encounters must lead to the same result. For disk clusters, the typical time interval between their encounters with GMCs is easily calculated to be about 3×10^8 years, which is close to the mean age of open clusters. This estimate provides further support for our arguments about the important part played by direct tidal disruption of open clusters as a result of their encounters with GMCs.

However, the situation with globular clusters is essentially different, because the condition (2) in this case plays the crucial part. High velocity dispersion of globular clusters (150 – 200 km s^{-1}) prevents their direct tidal disruption. Only multiple encounters with GMCs, which increase via tidal shocks the internal energy of the clusters, could account for some of their distruction. Let us now examine this process.

TIDAL SHOCKS AT HIGH-SPEED ENCOUNTERS

To estimate the total energy of a cluster, we use the Plummer model

$$E = -\frac{3\pi}{64}\frac{GM^2}{r_{hP}}. \quad (10)$$

According to Spitzer (1958), the change of the cluster energy, ΔE, as a result of a single encounter with a compact body of mass m, with impact parameter p and velocity V, is

$$\Delta E(p) = \left(\frac{4\alpha^2}{3}\right)\left(\frac{Gm}{p^2V}\right)^2 Mr_{hP}^2, \quad (11)$$

where α is the ratio of the rms distance of stars from the cluster center to r_{hP}. Impulse approximation in this form is valid only if the characteristic cluster-encounter time ($t_{enc} \equiv p/V$) is shorter that the dynamical time scale:

$$t_{dyn} \equiv \frac{\pi}{2}\left(\frac{2r_h^3}{GM}\right)^{1/2}. \quad (12)$$

We now equate these two time scales to obtain the maximum impact parameter:

$$p_{max} = 3.5V\left(\frac{r_{hP}^3}{GM}\right)^{1/2}. \quad (13)$$

At $p > p_{max}$ the tidal effect becomes adiabatic, making the gravitational shocks inefficient. We use (3)–(5) to obtain

$$p_{max} = 0.76R_p\left(\frac{V}{V_c}\right)\mathrm{dex}\{-3C/4\}. \quad (14)$$

We now determine the encounter velocity under the assumption that the GMC moves in a circular orbit in the Galactic plane, and the that cluster moves in a plane orbit with inclination i to the Galactic plane. Since the cluster usually crosses the Galactic plane near the pericenter of its orbit, we further assume that the cluster velocity is equal to its value at this point (V_p). We have for our adopted model (4) of the Galaxy

$$V_p^2 = (\varepsilon V_c)^2, \quad (15)$$

where

$$\varepsilon = \left[\frac{(1+e)^2}{2e}\ln\left(\frac{1+e}{1-e}\right)\right]^{1/2}. \quad (16)$$

Here $e \equiv (R_a - R_p)/(R_a + R_p)$ is the eccentricity, and R_a is the apogalacticon distance of the cluster orbit. The encounter velocity will then be

$$V^2 = V_c^2(1 + \varepsilon^2 - 2\varepsilon\cos i). \quad (17)$$

When deriving this relation, we took into account the extreme flatness of the system of molecular clouds: its full width at half-maximum density is ≃120 pc (Combes 1991). We therefore can consider this system to be absolutely flat when analyzing its interaction with clusters with $i \geq \arcsin(0.1 / 10\mathrm{kpc}) = 0\overset{\circ}{.}6$, i.e., virtually with all of the clusters.

We can now determine the minimum impact parameter, p_{min}, during the cluster lifetime, t, based on the orbital motion. The frequency of encounters with the impact parameter p is

$$d\nu = 2\pi p\left(\frac{\sigma_{H_2}}{m\sin i}\right)\left(\frac{2t}{P}\right)dp, \quad (18)$$

where σ_{H_2} is the surface density of molecular gas in the projection onto the Galactic plane; m is the mean mass of the cloud, and P is the orbital period of the cluster. For the isothermal sphere (4) the orbital period can be represented with sufficient accuracy as a Keplerian period with a mass in the range R_a and with a semimajor axis, $a = (R_a + R_p)/2$:

$$P = \frac{2\pi R_p}{\eta V_c}, \quad (19)$$

where $\eta \equiv (1 - e)(1 + e)^{1/2}$. We then obtain the following formula from the relation $\int_0^{p_{min}} d\nu = 1$:

$$p_{min} = \left(\frac{R_p m\sin i}{\eta V_c t\sigma_{H_2}}\right)^{1/2}. \quad (20)$$

It can be easily seen that the efficiency of gravitational shocks is determined by the closest encounters. However, the impulse approximation must be applied with caution to these encounters in view of finite sizes of the cluster and GMC. Numerical simulations showed that in the case of a cluster that flies by a compact mass the impulse approximation works for impact parameters $p = 5r_h$ (Binney and Tremaine 1987). However, it cannot be directly applied either to smaller p or in the cases where the characteristic cluster size is smaller than the cloud radius, r_g.

Earlier, several authors tried to extend the impulse approximation to the case of close and even penetrating encounters (Ahmad 1979; Binney and Tremaine 1987;

Theuns 1992). They showed this extension to be possible in principle, but the concrete formulas were obtained only for head-on encounters of clusters and clouds with a Plummer density distribution. However, the Plummer model parameters can be easily transformed into the King parameters, which are more commonly used to describe globular clusters. As a result, the change of the energy for a moderately concentrated cluster during its head-on encounter with a cloud can be described by classical formula (11), if we set $p \approx r_h$. Taking this into account, we can apply relation (11) for ΔE to encounters with compact objects with arbitrary impact parameters, adopting $\Delta E(p < r_h) \equiv \Delta E(r_h)$.

We use Eq. (8) to calculate the effective mass of the cloud that takes part in the encounter. We then apply (11) for $\Delta E(p)$ to determine the change of energy for various proportions of the basic linear parameters of the problem (p, p_{max}, r_g, r_h) in order to obtain an extended impulse approximation which is valid in the entire range of these parameters:

$$\frac{\Delta E}{\Delta E(r_g)} = \begin{cases} (r_g/p)^4; \quad p_{max} > p > \max\{r_g, r_h\} & \text{(a)} \\ [1-(r_g/p_{max})^2 + 2\ln(r_g/p)]^2 & \\ p_{max} > r_g > p > r_h & \text{(b)} \\ [2\ln(p_{max}/p)]^2; \quad r_g > p_{max} > p > r_h & \text{(c)} \\ [2\ln(p_{max}/r_h)]^2; \quad r_g > p_{max} > r_h > p & \\ [1-(r_g/p_{max})^2 + 2\ln(r_g/r_h)]^2 & \text{(d)} \\ p_{max} > r_g > r_h > p & \text{(e)} \\ (r_g/r_h)^4; \quad p_{max} > r_h > r_g > p & \text{(f)} \\ 0; \quad p_{max} < p. & \text{(g)} \end{cases} \quad (21)$$

We now determine the total change of the cluster energy during its lifetime, ΔE_{tot}, by integrating (21) over the impact parameter interval $[p_{max}, p_{min}]$:

(a) in the classical case, if $p_{max} > p_{min} > \max\{r_g, r_h\}$

$$\Delta E_{tot} = \Delta E(p_{min})\left(1 - \frac{p_{min}^2}{p_{max}^2}\right); \quad (22)$$

(b) if $p_{max} > r_g > p_{min} > r_h$;

$$\frac{\Delta E_{tot}}{\Delta E(r_g)} = \left(\frac{r_g}{p_{min}}\right)^2\left(6 - \frac{5r_g^2}{p_{max}^2} + \frac{r_g^4}{p_{max}^4}\right) - 5 + \frac{4r_g^2}{p_{max}^2} - \frac{r_g^4}{p_{max}^4} - 4\left(2 - \frac{r_g^2}{p_{max}^2} + \ln\frac{r_g}{p_{min}}\right)\ln\frac{r_g}{p_{min}}; \quad (23)$$

(c) if $r_g > p_{max} > p_{min} > r_h$;

$$\frac{\Delta E_{tot}}{\Delta E(r_g)} = 2\left(\frac{p_{max}}{p_{min}}\right)^2 - 2 - 4\ln\frac{p_{max}}{p_{min}} - 4\ln^2\frac{p_{max}}{p_{min}}; \quad (24)$$

(d) if $r_g > p_{max} > r_h > p_{min}$;

$$\frac{\Delta E_{tot}}{\Delta E(r_g)} = 2\left(\frac{p_{max}}{p_{min}}\right)^2 - 2\left(\frac{r_h}{p_{min}}\right)^2 - 4\ln\frac{p_{max}}{r_h} - \left(\frac{2r_h}{p_{min}}\right)^2\ln^2\frac{p_{max}}{r_h}; \quad (25)$$

(e) if $p_{max} > r_g > r_h > p_{min}$;

$$\frac{\Delta E_{tot}}{\Delta E(r_g)} = \left(\frac{r_g}{p_{min}}\right)^2\left(6 - \frac{5r_g^2}{p_{max}^2} + \frac{r_g^4}{p_{max}^4} - \frac{4r_h^2}{r_g^2} + \frac{2r_h^2}{p_{max}^2}\right) - 1 + \frac{2r_g^2}{p_{max}^2} - \frac{r_g^4}{p_{max}^4} - 4\left(1 + \frac{r_h^2}{p_{min}^2} - \frac{r_g^2}{p_{max}^2} + \ln\frac{r_g}{r_h}\right)\ln\frac{r_g}{r_h}; \quad (26)$$

(f) if $p_{max} > r_h > r_g > p_{min}$;

$$\frac{\Delta E_{tot}}{\Delta E(r_g)} = \left(\frac{r_g^2}{p_{min}}\right)^2\left(\frac{2}{r_h^2} - \frac{1}{p_{max}^2} - \frac{p_{min}^2}{r_h^4}\right); \quad (27)$$

(g) and, evidently, $\Delta E_{tot} = 0$ if $p_{max} < p_{min}$.

These formulas can be applied to various astrophysical problems provided that the density distribution in the body producing a tidal shock is similar to that of a GMC ($\rho \sim r^{-1}$) and the body receiving this shock can be described by a Plummer model or a King model with a moderate concentration ($0.8 \le C \le 1.6$).

In subsequent calculations, we do not try to attain the unjustifiably high accuracy and therefore restrict the above expressions to their limiting cases:

$$\frac{\Delta E_{tot}}{\Delta E(r_g)} \approx \begin{cases} (r_g/p_{min})^4; \quad p_{max} > p_{min} > \max\{r_g, r_h\} & \text{(a)} \\ 6(r_g/p_{min})^2; \quad p_{max} > r_g > p_{min} > r_h & \text{(b)} \\ 2(p_{max}/p_{min})^2; \quad r_g > p_{max} > p_{min} > r_h & \text{(c)} \\ 2(p_{max}/p_{min})^2; \quad r_g > p_{max} > r_h > p_{min} & \text{(d)} \\ 6(r_g/p_{min})^2; \quad p_{max} > r_g > r_h > p_{min} & \text{(e)} \\ 2r_g^4/(r_h p_{min})^2; \quad p_{max} > r_h > r_g > p_{min} & \text{(f)} \\ 0; \quad p_{max} < p_{min}. & \text{(g)} \end{cases} \quad (28)$$

We consider the following condition to be the criterion for the cluster disruption:

$$\Delta E_{tot} = -E. \quad (29)$$

We then substitute the expressions for the corresponding quantities from (3)–(5) and (10)–(11) into (29)

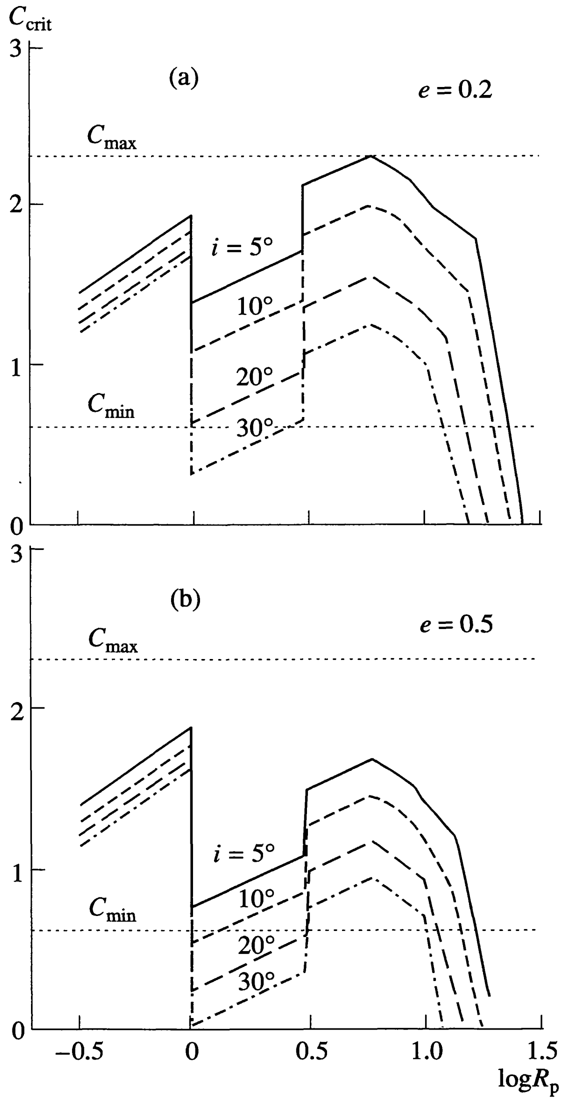

Fig. 1. The critical cluster concentration parameter, C_{crit}, as a function of the perigalacticon distance, R_p, in kiloparsecs, the orbital inclination to the Galactic plane, i, and eccentricity, e. Dotted horizontal lines show the maximum (C_{max}) and minimum (C_{min}) concentrations of the observed clusters.

to see that in all cases except (f) the only remaining cluster parameter is its concentration. We solve (29) for C to obtain the critical concentration value:

case (a):

$$C_{crit} = \frac{4}{3}\log\left(\frac{\alpha G t \eta \sigma_{H_2}}{V \sin i}\right) - 0.25; \qquad (30)$$

cases (b) and (e):

$$C_{crit} = \frac{2}{3}\log\left(\frac{G^2 m \eta \alpha^2 t R_p \sigma_{H_2}}{V_c r_g^2 V^2 \sin i}\right) + 0.27; \qquad (31)$$

cases (c) and (d):

$$C_{crit} = \frac{1}{3}\log\left(\frac{G^2 m R_p^3 \eta \alpha^2 t \sigma_{H_2}}{r_g^4 V_c^3 \sin i}\right) - 0.1; \qquad (32)$$

case (f):

$$C_{crit} = 2\log\left(\frac{G^{4/3} m t \eta V_c^{1/3} \sigma_{H_2}}{M^{2/3} V^2 R_p^{1/3} \sin i}\right) + 1.1. \qquad (33)$$

The condition for the globular cluster disruption is the inequality $C \le C_{crit}$. We point out again that in all cases except (f) C_{crit} for clusters moving in identical orbits is independent of the cluster mass. This fact suggests that we must look for a relation between the concentrations of globular clusters and their orbital elements: it is through this relation that the cluster–GMC interaction might manifest itself.

ENCOUNTERS WITHIN THE GALACTIC DISK

In subsequent calculations, we adopt $V_c = 200$ km s^{-1}, $t = 16 \times 10^9$ years, $\alpha = 1$, and the following simple expression for σ_{H_2}, which describes rather accurately the distribution of molecular matter in the Galactic disk (Sanders *et al.* 1984; Robinson *et al.* 1988):

$$\sigma_{H_2}(R) = \begin{cases} 300 M_\odot\ \text{pc}^{-2}; & R < 0.8 \text{ kpc} \\ 5 M_\odot\ \text{pc}^{-2}; & 0.8 \text{ kpc} < R < 3 \text{ kpc} \\ 20 M_\odot\ \text{pc}^{-2}; & 3 \text{ kpc} \le R \le 6 \text{ kpc} \\ 148\exp\{-R/3 \text{ kpc}\} M_\odot\ \text{pc}^{-2}; & R > 6 \text{ kpc}. \end{cases} \qquad (34)$$

A well-known peculiarity of this distribution is that most of GMCs are concentrated in two 'reservoirs': the central molecular disk (about 10% of the total mass) and the molecular ring (about 80% of the total mass). We assume the mean GMC mass to be $m = 5 \times 10^5 M_\odot$ and $m = 2 \times 10^6 M_\odot$ beyond the central disk (i.e., at $R > 0.8$ kpc) and within it ($R < 0.8$ kpc), respectively, and the mean GMC radius to be $r_g = 20$ pc throughout the entire Galaxy (Blitz 1993).

We now determine the applicability domains for various versions of (28). To this end, we consider a cluster of typical mass $M = 10^5 M_\odot$ and concentration $1 < C < 2$ moving in a moderately eccentric ($e \approx 0.3$) orbit with inclination $5° \le i \le 30°$. Here the domain of substantial dynamical GMC–cluster interaction effect is restricted to such orbits. The calculations show that, depending on R_p, different variants of (28) can be realized:

(d) $R_p < 1$ kpc

(e) 1 kpc $\le R_p \le$ 10 kpc

(a) 10 kpc $\le R_p \le$ 3 kpc

(g) $R_p > 30$ kpc

Versions (b), (c), and (f) cannot be realized. In view of this circumstance, we can derive the following $C_{crit}(R_p)$ relation which is parametrized by the inclination and eccentricity of the orbit:

$$C_{crit}(<1\text{ kpc}) = 1.6 + \log\frac{R_p}{1\text{ kpc}} + \frac{1}{3}\log\frac{\eta}{\sin i}, \quad (35)$$

$$C_{crit}(1\text{–}10\text{ kpc}) = -0.6 + \frac{2}{3}\log\left\{\left(\frac{R_p}{1\text{ kpc}}\right)\left(\frac{\sigma_{H_2}}{1(M_\odot\text{ pc}^{-2})}\right)\frac{\eta}{\gamma\sin i}\right\}, \quad (36)$$

$$C_{crit}(10\text{–}30\text{ kpc}) = -0.8 + \frac{4}{3}\log\left\{\left(\frac{\sigma_{H_2}}{1M_\odot\text{ pc}^{-2}}\right)\frac{\eta}{\gamma^{1/2}\sin i}\right\}, \quad (37)$$

where $\gamma \equiv 1 + \varepsilon^2 - 2\varepsilon\cos i$. This relation is illustrated in Fig. 1. Here we used moderately eccentric orbits as an example: $e = 0.2$ in Fig. 1a and $e = 0.5$ in Fig. 1b. The inclination of the orbit (in degrees) varies from 5° to 30°. At $i >$ (30°–40°) the interaction between globular clusters and GMCs becomes inefficient everywhere except for the central molecular disk. At $i < 5°$ the flat-orbit approximation that we use here becomes unsatisfactory because of the influence of the Galactic disk potential.

Thus, the disruptive effect of tidal shocks produced by molecular clouds is quite tangible for clusters moving in moderately elongated and inclined orbits. This effect, as expected, reaches its maximum degree in the central molecular disk ($R < 0.8$ kpc) and molecular ring (3 kpc $\le R \le$ 10 kpc) regions. However, the conditions for the cluster-GMC interaction in these regions of the Galaxy are essentially different: the tidal shocks in the central disk occur only when the cloud directly collides with and penetrates through the GMC, whereas in the molecular ring, the most important encounters are the remote encounters involving no penetration of the cluster into the GMC. Correspondingly, the dependence of the interaction efficiency on the problem parameters is different for the two cases: in particular, encounters in the central disk are much less sensitive to the shape and orientation of the cluster orbit.

It would be interesting to calculate C_{crit} for each cluster and compare it with the observed concentration, C_{obs}. Unfortunately, the accurate orbital parameters of clusters are unknown. We can infer them only indirectly from the observed position of the cluster and its structural parameters. We took cluster data from the catalogs by Djorgovski (1993), Trager *et al.* (1993), and Harris (1994) adopting $M/L_V = 3$ and the distance to the Galactic center, $R_0 = 8.5$ kpc. Based on these data, we use (3) to calculate perigalacticon distances, R_p, and minimum eccentricities of cluster orbits, $e_{min} = (R - R_p)/(R + R_p)$, where R is the observed distance from the cluster to the Galactic center. We estimated the

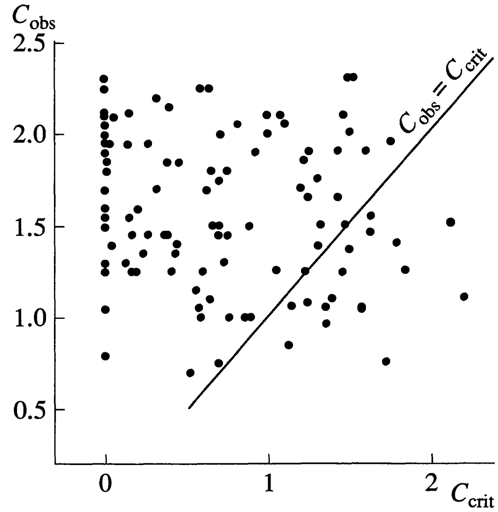

Fig. 2. The position of Galactic globular clusters on the C_{obs}–C_{crit} diagram, where C_{obs} is the observed concentration and C_{crit} is the minimum concentration required for the cluster to be stable against tidal shocks. $C_{crit} = 0$ is adopted for clusters with formally calculated $C_{crit} < 0$.

orbital inclination to the Galactic plane from the $|Z|/R$ ratio, where Z is the distance of the cluster from the Galactic plane. Because of the boxlike shapes of cluster orbits, resulting from different frequencies of orbital motion and oscillations about the Galactic plane, the $|Z|/R$ ratio in most of cases gives us a lower limit for sin i. The same is true for e_{min} and e. As a result, this ratio yields overestimated C_{crit} values and therefore we cannot expect the C_{crit} values thus calculated to satisfy the inequality $C_{obs} > C_{crit}$, which follows from the cluster survival condition. However, we can expect most of the clusters to satisfy this inequality because in the majority of cases our estimates for e_{min} and sin i are, in fact, close to their true values (Surdin 1996).

Figure 2 shows the distribution of 120 clusters on the C_{crit}–C_{obs} plane. Only 17 of them do not satisfy the condition $C_{obs} > C_{crit}$, which even formally is not absolutely rigorous: a cluster crossing the $C_{crit} = C_{obs}$ line does not disappear immediately but only has its disruption accelerated. An important feature of this distribution is the proximity of a large number of clusters to the $C_{crit} = C_{obs}$ line and the abrupt decrease in the number of clusters at $C_{crit} < C_{obs}$. Figure 3 clearly demonstrates this effect. This diagram strongly suggests that the effect which we discussed here is very important for many clusters.

Another evidence for the disruptive action of GMC on the system of globular clusters follows from a comparison of the R_p distribution for clusters with the surface density distribution of molecular matter in the

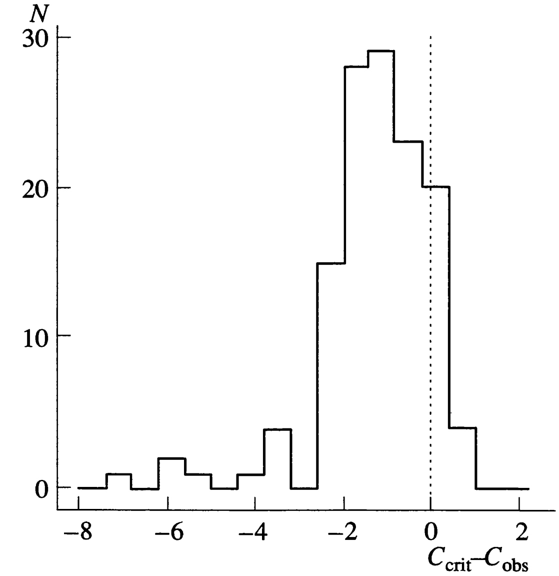

Fig. 3. The distribution of the cluster distances from the critical-concentration line.

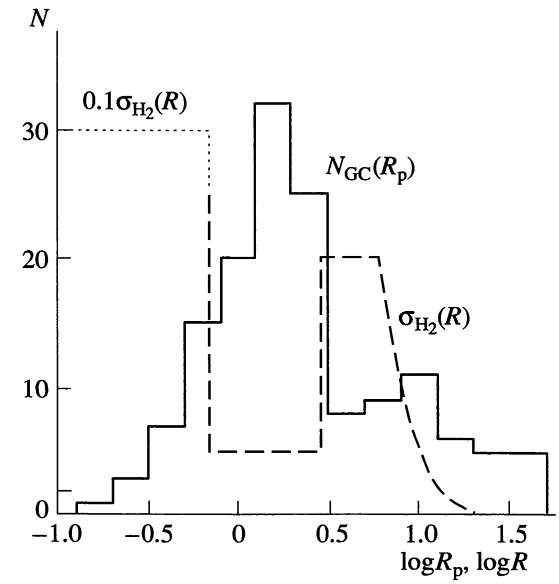

Fig. 4. The surface density of molecular gas, σ_{H_2} (in $M_\odot$ pc^{-2}), as a function of the Galactocentric distance, R, and the number of globular clusters, N_{GC}, as a function of the perigalacticon distances of their orbits, R_p. All distances are in kpc.

Galactic disk (Fig. 4). The obvious anticorrelation of these distributions leaves no doubts about the substantial influence of GMCs on the dynamical evolution of globular clusters.

CONCLUSIONS

We used our extended version of the impulse approximation to analyze the role of tidal shocks produced by giant molecular clouds on globular star clusters. The general formulas that we obtained in this paper make it possible to study the efficiency of the process in any disk galaxy. In most of the cases, the degree of star concentration at the cluster center is the only physical parameter of the cluster that determines its stability against tidal shocks. The cluster stability also depends to a considerable degree on the parameters of its orbit.

The present-day state of the molecular cloud population in the Galactic disk allows the above interaction to appreciably manifest itself only among globular clusters that move in low-eccentricity, low-inclination orbits. However, in the past, the degree of star concentration at the cluster center was much lower and the system of molecular clouds was much more populated than at present. Therefore, the average globular cluster–GMC tidal interaction efficiency over the entire period of the Galaxy evolution must have been much higher than it is at present. That might be the reason why the manifestations of this interaction can be easily seen in the distribution of concentrations (Figs. 2 and 3) and Galactocentric distances (Fig. 4) of clusters.

The comparison of morphological parameters of clusters with prograde and retrograde (relative to the Galactic rotation) orbits can be used as an important criterion for the efficiency of the globular cluster – GMC interaction. It follows from our analysis that clusters with retrograde orbits (i.e., with $i > 90°$) are virtually unaffected by the disruptive action of GMCs. However, this test requires prior mass determination of accurate proper motions of clusters.

The disruptive action of GMCs, of course, is not among the important effects of the dynamical evolution of globular clusters, such as dissipation, dynamical friction, compressive gravitational shocks at the crossing of the Galactic disk, and some other internal and external effects (Matsunami *et al.* 1959; Surdin 1978, 1979; Aguilar *et al.* 1988; Chernoff and Weinberg 1990; Surdin 1995, and Gnedin and Ostriker 1996). It now turns out, however, that any coherent analysis of the dynamical evolution of globular clusters would be substantially incomplete if it does not allow for GMC-related effects.

Inhomogeneous GMC distribution in the Galactic disk gives rise to some peculiar features in the distribution of the globular-cluster parameters. The globular-cluster system as a whole is much more stable and conservative than the GMC system and therefore determining its properties (first of all, the orbital parameters of clusters) might allow us to reconstruct to a certain degree the history of the GMC population.

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