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Survival and disruption of galactic substructure

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Summary. We consider the tidal and evaporative disruption of an initial spectrum of galactic substructure which is here assumed to span a wide range of masses and sizes. The survival of subclusters having masses comparable with those of known globular clusters is best explained if the initial distribution was one of roughly constant surface brightness. Some recent observations on the relationship between the properties of globular clusters and their parent galaxies have a natural explanation within this context.

1 Introduction

A remarkable characteristic of most galaxies is their relatively amorphous structure. Apart from globular clusters, they seldom if ever show signs of having bound substructures with more than a few thousand stars. Furthermore, the globular clusters they do possess are usually few in number and have masses and radii which lie within a rather narrow range. For example, in our Galaxy it has been estimated that there are only about 200 globular clusters (Harris 1976) and they have masses and radii which span only two orders of magnitude or less. With reference to these facts Peebles & Dicke (1968) have called attention to the similarity between globular cluster masses and the Jeans mass at (re)combination and have suggested that galaxies may result from the agglomeration of such protoclusters, many of which would have been destroyed in the process by collisions. Alternatively, Tremaine (1975) and others have pointed out that stellar evaporation and tidal disruption may have destroyed many globular clusters.

A seemingly unrelated curiosity is the fact that the surface brightnesses of globular clusters are comparable with those of galaxies, yet their masses are typically smaller by about six orders of magnitude. In fact, the characteristic (half-light) surface brightnesses in Peterson & King's (1975) and Peterson's (1976) lists of globular clusters are comparable with those in Oemler's (1976) list of elliptical galaxies (a few times $10^3 L_\odot\,\mathrm{pc}^{-2}$). In part, this may be due to a selection effect of the kind recently emphasized by Disney (1976). In this note we point out that both the structural uniformity and small numbers of globular clusters and the similarity of their surface brightnesses to those of galaxies may have a common dynamical explanation even if the initial spectrum of Galactic substructure had no characteristic scale. The basic idea is illustrated in Fig. 1 and has already been summarized by Rees (1977) in

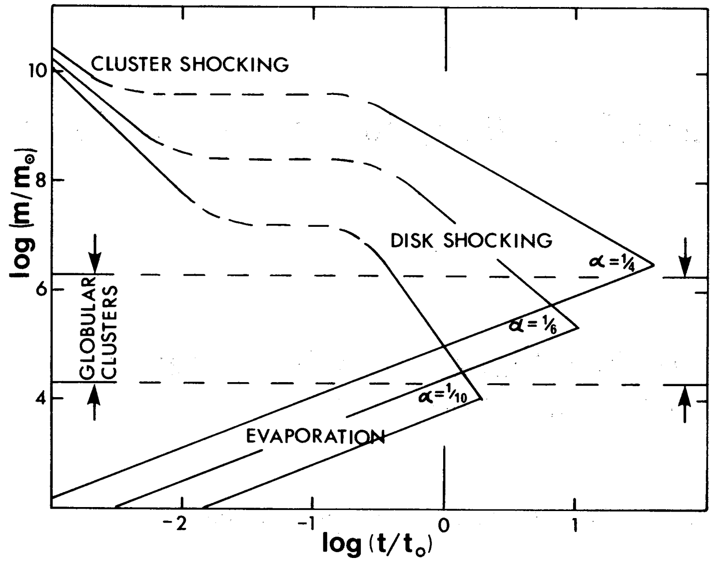

Figure 1. Evaporative and tidal disruption as a function of time t. Solid lines indicate $t = t_{\mathrm{shc}}$ (equation 1), $t = t_{\mathrm{shd}}$ (equation 2) and $t = t_{\mathrm{ev}}$ (equation 3) for three values of α. The axes have been labelled for the particular case that $M = 1.4 \times 10^{11} m_\odot$, $T_{\mathrm{c}} = 6 \times 10^7$ yr and $\lambda = \omega = 1$.

a slightly different form. The result is that stellar evaporation and tidal shocking would have erased all substructure except known globular clusters only in the case that the initial distribution of subclustering was one of roughly constant surface brightness.

2 Disruptive effects

We begin by assuming that shortly after its formation the Galaxy consisted of bound stellar subclusters spanning a much wider range of sizes than presently observed globular clusters. For simplicity we shall assume that the characteristic densities and masses of these subclusters varied as $\rho \propto m^{-3\alpha}$, the constant of proportionality being chosen to give equality for galactic parameters. We then consider their disruption and survival in terms of the parameter α (which in all realistic cases is positive). Before proceeding it is worth noting that $\alpha = 1/6$ corresponds to constant surface brightness and that the above mass-density relation would develop gravitationally from an initial subgalactic fluctuation spectrum of the form $\delta\rho/\bar{\rho} \propto m^{-\alpha}$. The arguments which follow, however, do not depend critically on the order in which the galaxy and its substructure formed. For the moment we shall also assume that small clusters were not bound within larger ones as would be the case in a strict hierarchy of subclustering. In what follows we denote cluster masses (total), characteristic radii (half-mass) and crossing times by m, r and t_{c} respectively and the corresponding quantities for the Galaxy by M, R and T_{c}. When necessary, we shall take 'crossing times' to be twice the 'dynamical time-scale' defined by Spitzer & Hart (1971); thus t_{c} is $3.2 r^{3/2} (Gm)^{-1/2}$.

The first disruptive effect to be considered is tidal shock heating. Close encounters of clusters will impulsively pump energy into their internal (stellar) motions and cause disruption on the timescale

$$t_{\mathrm{shc}} \simeq {}^1\!/_{14} (T_{\mathrm{c}}/f)(R/r) \simeq {}^1\!/_{14} (T_{\mathrm{c}}/f)(M/m)^{\alpha + 1/3} \tag{1}$$

where f is the fraction of mass in undisrupted clusters (Spitzer & Chevalier 1973). The coefficient $1/14$ has been derived specifically for the case that $\alpha = 1/6$ (Spitzer 1958) and will be adequate for the values of α to be considered below. As Ostriker, Spitzer & Chevalier (1972) have pointed out, a similar effect occurs as clusters pass through the galactic disk, causing disruption on the timescale

$$t_{\rm shd} \simeq 6(T_c/d)\,(t_c/10^8\,{\rm yr})^{-2} \simeq 6 \times 10^8\,{\rm yr}\,(dT_c/10^8\,{\rm yr})^{-1}\,(M/m)^{3\alpha} \qquad (2)$$

where d is the ratio of the disk's mass density where clusters typically cross it (see below) to its present value in the solar neighbourhood. The coefficient 6 adopted here includes the extra factor of ½ noted by Spitzer & Chevalier (their $1/\beta$) but apart from this it agrees with that of Ostriker *et al.* when T_c is set equal to half the characteristic orbital period (their P_c). Note that both tidal effects disrupt large clusters first.

The other disruptive effect to be considered is stellar evaporation. As a cluster relaxes some of its stars will gain energy and escape, causing the cluster to lose mass on the timescale $\gamma t_{\rm rh}$ where $t_{\rm rh}$ is the 'reference' relaxation timescale and γ is a parameter which depends on cluster structure and stellar mass function but typically lies in the range 20--70 (Spitzer & Chevalier 1973; Spitzer & Shull 1975). Since $t_{\rm rh}$ is $n/52\log(0.4n)$ times t_c where n is the number of stars in the cluster (Spitzer & Hart 1971), the evaporation timescale may be put into the convenient form

$$t_{\rm ev} \simeq {}^1\!/_{260}\,\gamma\, t_c\,(m/\mu) \simeq {}^1\!/_{260}\,\gamma\, T_c(M/\mu)\,(m/M)^{1+3\alpha/2}. \qquad (3)$$

Here μ is the mean stellar mass and the slowly varying logarithmic factor has been set to 5. Note that evaporation disrupts small clusters first.

Fig. 1 illustrates the times at which these effects become important for different masses and their dependence upon α. Very early in the history of the Galaxy a disk may or may not have been present (corresponding to d of order unity or zero) but in any case cluster encounters would have been the most important disruptive effect. Once most of the mass in clusters has been disrupted ($f \ll 1$) cluster encounters cease to be important. The exact time at which this occurs depends on the initial distribution of cluster masses but we shall not need to know it since disruption at present is dominated by disk shocking and evaporation. Thus, the α-dependent range of surviving masses may be estimated by setting both $t_{\rm shd}$ and $t_{\rm ev}$ equal to t_0, the age of the Galaxy, and using the second parts of (2) and (3):

$$[3.1 \times 10^{-9}\lambda(1.4 \times 10^{11} m_\odot/M)\,(6 \times 10^7\,{\rm yr}/T_c)]^{1/(1+3\alpha/2)} \lesssim m/M \lesssim [(\omega/8.5)\,(6 \times 10^7\,{\rm yr}/T_c)]^{2/3\alpha} \qquad (4)$$

$$\lambda \equiv (40/\gamma)\,(t_0/1.2 \times 10^{10}\,{\rm yr})\,(\mu/{}^1\!/_3 m_\odot), \quad \omega \equiv (200T_c/t_0)^{1/2}(6/d)^{1/2}. \qquad (5)$$

The reasons for adopting this form will become apparent shortly. Note that if α is too small then no clusters will survive to the present and that if α is too large then too many clusters will survive.

The above mass range is given in Table 1 below for $M = 1.4 \times 10^{11} m_\odot$, $T_c = 6 \times 10^7$ yr and for three values each of α, λ and ω. This crossing time is consistent with a half-mass radius of $R \simeq 6$ kpc for the globular cluster system (Harris 1976; Table VI) and orbital velocities between 200 and 300 km/s (depending upon the eccentricity). Note that the fiducial value of d has been taken to be 6 from Innanen's (1966) estimate of the disk's density at 4 kpc (in order to allow for moderate eccentricities). When α is small the minimum mass is fairly sensitive to α but not to reasonable variations of T_c and λ and even less to variations in M. The maximum mass, however, is rather sensitive to T_c and ω and should therefore be given less weight in estimating α. A comparison of the table with Fig. 2 indicates that $\alpha \simeq 1/6$

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Table 1. Logarithms of surviving cluster mass range (in units of $m_\odot$) for $M = 1.4 \times 10^{11} m_\odot$ and $T_c = 6 \times 10^7$ yr (*cf.* equation (4)); top row: $\alpha = 1/10$; middle row: $\alpha = 1/6$; bottom row: $\alpha = 1/4$. Figures in parentheses indicate no surviving clusters.

ω \ λ	1/3	1	3
1/3	(3.3–1.7)	(3.8–1.7)	(4.2–1.7)
	4.0–5.5	4.4–5.5	4.7–5.5
	4.6–7.4	5.0–7.4	5.3–7.4
1	3.3–5.0	3.8–5.0	4.2–5.0
	4.0–7.4	4.4–7.4	4.7–7.4
	4.6–8.7	5.0–8.7	5.3–8.7
3	3.3–8.1	3.8–8.1	4.2–8.1
	4.0–9.3	4.4–9.3	4.7–9.3
	4.6–9.9	5.0–9.9	5.3–9.9

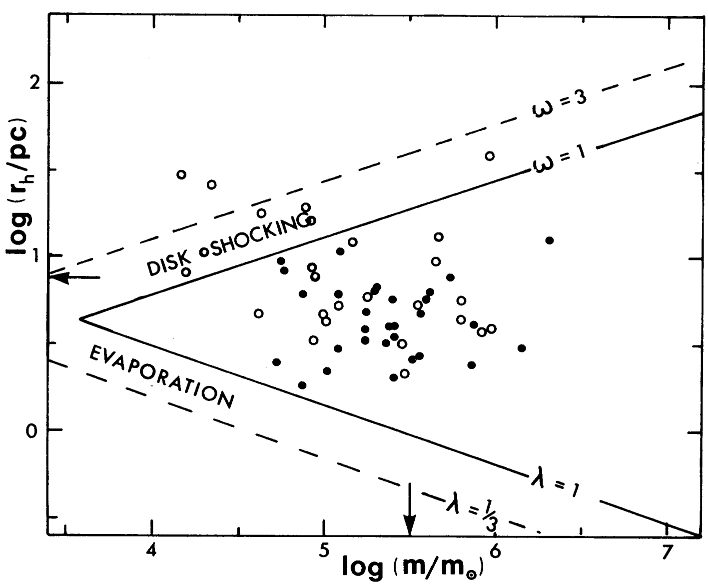

Figure 2. Present mass–radius distribution of globular clusters. Filled circles represent all entries in the Peterson–King (1975) and Peterson (1976) lists (PK) with measured core and tidal radii (r_c and r_t) and Galactocentric distance less than 10 kpc (Harris 1976). Open circles represent the corresponding entries with Galactocentric distances greater than 10 kpc. Half-mass radii were taken to be $r_h \simeq 0.70\,(r_c r_t)^{1/2}$ (an excellent approximation for King's (1962) model) and total masses were taken to be 1.6 times those given by PK (Illingworth 1976). Diagonal lines are lines of constant $t_{\rm shd}$ and $t_{\rm ev}$ (equation 6) and arrows indicate mean masses and radii.

(or perhaps slightly less) is most compatible with the actual mass range of globular clusters (approximately $2 \times 10^4 m_\odot$ to $2 \times 10^6 m_\odot$). We note that this value of α is also consistent with the above galactic mass and characteristic radius and the mean mass ($3.2 \times 10^5 m_\odot$) and radius (7.4 pc) of clusters represented in Fig. 2.

As a check on the consistency of the assumption that the parameters λ and ω are both of order unity some additional information from Fig. 2 can be exploited. Using the first parts of (2) and (3) and once again setting $t_{\rm shd}$ and $t_{\rm ev}$ to t_0 gives the following α-*in*dependent mass–radius constraints

$$67\lambda^{2/3}(m/m_\odot)^{-1/3} \lesssim r/\text{pc} \lesssim 0.28\,\omega^{2/3}(m/m_\odot)^{1/3}. \tag{6}$$

Since λ and ω appear in both (4) and (6) only those combinations of γ, μ, d, T_c and t_0 appearing in (5) need be considered. This is analogous to the method used by Lightman, Press & Odenwald (1977) in their recent study of core collapse times. The above constraint is drawn in Fig. 2 for several values of λ and ω. (A similar diagram and its interpretation in terms of evaporative and disk-shocking processes has also been given by Tremaine (1975).) Since all of the upper left most points correspond to very distant clusters (which should be little affected by disk shocking) $\lambda \simeq \omega \simeq 1$ is clearly satisfactory on these grounds. It is also consistent with reasonable values for the other parameters appearing in (5). Note that although the globular clusters represented in Fig. 2 show no particular tendency to lie along a line of constant surface brightness, this would not be expected since, by hypothesis, they represent only a small fraction of the initial distribution and in any case would have evolved somewhat from their initial positions on the diagram.

3 Discussion

The foregoing treatment has neglected several effects which we shall now briefly mention. Firstly, we have ignored the collisions of protoclusters while still in the gaseous phase. Disruption by encounters in this phase is roughly $(M/m)^{2/3-\alpha}$ times more efficient than in the stellar phase and would have preferentially destroyed small protoclusters at very early times. Secondly, we have ignored the possibility that initially many smaller subclusters may have been bound within larger subclusters, thus increasing their rate of disruption by encounters. Had these effects been important for more than a few galactic crossing times, *all* scales of subclustering would have been destroyed; our calculations of recent disruption rates would not, however, be affected. Thirdly, Tremaine, Ostriker & Spitzer (1975; see also Tremaine 1976) have suggested that dynamical friction would have caused large clusters to have spiralled towards the centre of the Galaxy where they would be tidally disrupted. This process, however, operates on a timescale of order $\frac{1}{30} T_c(M/m)$ and would therefore only affect clusters larger than about $3 \times 10^7 m_\odot$. Since both cluster and disk-shocking timescales are shorter than this for larger m and $\alpha < \frac{1}{3}$, the disruption of clusters before they reach the galactic nucleus may place some constraints on how many clusters could have contributed to its mass by dynamical friction.

It is also interesting to consider the role of disruptive effects in other galaxies. Clearly, the absence of a disk in ellipticals would permit the survival of more massive clusters than in spirals and this systematic effect may in part account for the relatively small distance modulus of Virgo galaxies recently obtained by Hanes (1977) on the assumption that globular clusters are good 'standard candles'. Furthermore, if it is assumed that the crossing times of galaxies also vary with their masses as $M^{3\alpha/2}$ then (4) indicates that for any value of α, the smallest surviving cluster mass should be independent of the parent galaxy's mass. In the case of spirals, the disk strength d should vary as M and the maximum surviving mass as $M^{1/2-1/3\alpha}$ or $M^{-3/2}$ when $\alpha = 1/6$ (*cf.* equations (4) and (5)).

Finally, we note that the initial fluctuation spectra considered here are rather different from those proposed by Peebles (1974) ($\alpha \simeq \frac{1}{2}$) and Gott & Rees (1975) ($\alpha \simeq \frac{2}{3}$) for the initial distribution of matter on scales larger than individual galaxies. However, as Rees & Ostriker (1977) have recently emphasized, the processes giving rise to structure on galactic and subgalactic scales may be quite different from those on larger scales. In conclusion, the mass-density relation favouring the survival of clusters in the appropriate mass range is quite consistent with the velocity dispersion and surface brightness data on globular clusters and galaxies and may be related to Fish's (1964) and Freeman's (1970) suggestions that the central surface brightnesses of (well-studied) galaxies lie within two fairly narrow ranges. It must be emphasized though that no satisfactory physical explanation has yet been given for the origin of such a distribution.

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