Tidal Tails Around 20 Galactic Globular Clusters: \*,\**

Observational Evidence for Gravitational Disk/Bulge Shocking.

Stéphane Leon\textsuperscript{1,2,3}, Georges Meylan\textsuperscript{4} & Françoise Combes\textsuperscript{1}

\textsuperscript{1} DEMIRM, Observatoire de Paris, 61, Avenue de l’Observatoire, F-75014 Paris, France
\textsuperscript{2} CAI, Observatoire de Paris, 61, Avenue de l’Observatoire, F-75014 Paris, France
\textsuperscript{3} Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 1-87, Nankang, Taipei, Taiwan
\textsuperscript{4} ESO, Karl-Schwarzschild-Strasse 2, D-85748 Garching, Germany

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Abstract. Large-field multi-color images of 20 galactic globular clusters are used to investigate the presence of tidal tails around these stellar systems. Field and cluster stars are sorted with the help of color-magnitude diagrams, and star-count analysis is performed on the selected cluster stars in order to increase the signal-to-noise ratio of their surface density. We study the overdensities of these stars using the wavelet transform of the star counts in order to filter the background density noise and to detect the weak structures, at large scale, formed by the numerous stars previously members of the clusters. We associate these stellar overdensities with the stars evaporated from the clusters because of dynamical relaxation and/or tidal stripping from the clusters by the galactic gravitational field. We take into account the strong observational biases induced by the clustering of galactic field stars and of background galaxies, along with the fluctuations of the background due to dust extinction.

Most of the globular clusters in our sample display strong evidence of tidal interactions with the galactic plane in the form of large and extended deformations. These tidal tails exhibit projected directions preferentially towards the galactic center. All the clusters observed, which do not suffer from strong observational biases, present such tidal tails, tracing their dynamical evolution (evaporation, tidal shocking, tidal torquing, and bulge shocking) in the Galaxy. The clusters exhibit different regimes of mass loss rate, detected using the radial density slope in the outer parts of the clusters. For NGC 5139 (\(\omega\) Centauri), we estimate, taking into account the possible presence of mass segregation in its outer parts, that about 0.6 to 1 \% of its mass has been lost during the current disk shocking event. In the case of NGC 6254, we tentatively estimate, in the cluster reference frame, for the radial diffusion velocity of the stars stripped, a value of the order of the velocity dispersion in the cluster itself. The sizes and orientations of these observed tidal tails are perfectly reproduced by N-body simulations of globular clusters in the galactic potential well. We present these results in a companion paper (Combes, Leon & Meylan 1999).

As a by-product of this study, we detect several new galaxy clusters towards the different fields studied at high galactic latitude. The estimation of the tidal radius of some of the globular clusters could have been overestimated because of these galaxy clusters.

Key words: Techniques: image processing, ISM: dust, extinction, Globular clusters: general–individual, Galaxy: structure, Cosmology: large-scale structure of Universe

1. Introduction

Recent works have emphasized that globular clusters (GCs) are stellar systems which exhibit strong dynamical evolution in the potential well of their host galaxy (Gnedin & Ostriker 1997, hereafter GO97, Murali & Weinberg 1997). Since their birth, GCs suffer internal evolution on their own: at the very beginning GCs evolve rapidly because of the fast stellar evolution of their massive stars (Vesperini & Heggie 1997, Portegies Zwart et al. 1997). The finite size of the GCs produces two-body relaxation between the member stars; equipartition of energy heats the lighter stars which diffuse outwards into the halo while the heavier stars sink slowly towards the contracting core (Spitzer & Hart 1971). Typically, the relaxation time \(t_{rh}\) (hereafter we will refer to the relaxation time at the half mass radius; see, e.g., Binney & Tremaine 1987) in a GC is of the order of \(t_{rh} = 10^9\) yr (GO97), which is significantly less than the age of all galactic globular clusters.
Owing to the negative specific heat in self-gravitating stellar systems (Antonov 1962, Lynden-Bell & Wood 1968), related to the virial equilibrium, the core is contracting monotonically during a process called the “gravothermal catastrophe”, leading to core collapse, characterized by very high stellar densities (up to $10^6 M_\odot pc^{-3}$). It has been eventually recognized that this process is not so catastrophic after all, since the cluster core does not collapse for ever but bounces back towards lower stellar density phases (Hénon 1975). The key role of binaries (either primordial or formed via encounters during the high stellar density phase) has been emphasized in the internal dynamics of the GCs: these binaries act as a heating source and slow down the core collapse (Goodman & Hut 1989) and even reverse it. Many authors have studied numerically the post core-collapse phase, using conducting-gas-sphere, Fokker-Planck, and N-body codes, in simulations computed well into core collapse and beyond, leading to the discovery of possible post-collapse gravothermal oscillations (see Meylan & Heggie 1997 for a review). Globular clusters evolve dynamically, even when considering only relaxation, which causes stars to escape, consequently cluster cores to contract and envelopes to expand.

Any galaxy through its gravitational potential well influences the dynamical evolution of its globular clusters, accelerating their destruction. The stars in the globular cluster halo are stripped by the tidal field of the galaxy: the outward diffusion of the stars towards the sub-thermally speeded up and the core contracts even more (Spitzer & Chevalier 1973). Moreover the gravitational shocks heat up the outer parts of the globular cluster, increasing its loss of stars (Aguilar et al. 1988, Weinberg 1994, Kundic & Ostriker 1995, Leon et al. 2000). Shocks are caused by the tidal field of the galaxy: interactions with the disk, the bulge and, at a lower level, with the giant molecular clouds (GMCs, see Spitzer 1958), heat up the outer regions of each star clusters. The disk-shocking occurs when the GC crosses the thin disk where it is compressed by the varying $z$-component of the galactic plane potential; this has been found to dominate the heating of GCs (Chernoff et al. 1986). A GC globally gains energy during the crossing and exhibits peculiar transient deformation (Leon et al. 2000). The shocks with the bulge and the GMCs are similar in their physical processes; the GCs suffer an elongation aligned parallel to the density gradient in the bulge or the GMC. These processes combined with the internal dynamical evolution have probably destroyed an important fraction of the primordial GCs and are still currently at play. GO97 estimate that “half of the present clusters are to be destroyed within the next Hubble time”.

All GCs are expected to have already lost an important fraction of their mass, deposited in the form of individual stars in the halo of the Galaxy. The mass-loss rate is a function of the total mass of the cluster, its structural parameters like the concentration $c$ (where $c = \log (r_t/r_c)$), with $r_t$ and $r_c$ are the tidal and core radii), and its orbital motion around the galactic center. Till recently, the only way to investigate the orbital history of a globular cluster, apart from proper motions, was to derive its tidal radius $r_t$, which gives an indication of its perigalactic distance. Unfortunately, there are difficulties in defining the tidal radius, both theoretically and observationally; and, as expected, there are discrepancies between the theoretical and observational values of the tidal radius (see, e.g., Odenkirchen et al. 1997, Scholz et al. 1998).

N-body simulations of globular clusters embedded in a realistic galactic potential (Oh & Lin 1992; Johnston et al. 1997; Combes, Leon & Meylan 1999, hereafter CLM99) have been performed in order to study the amount of mass loss for different kinds of orbits and different kinds of clusters, along with the dynamics and the mass function in tidal tails. The 2-D structure of such tidal tails appears to be a good tracer of gravitational shocks and should be a tracer of the potential well. Moreover the detection of unbound stars released by the clusters is the only way to measure directly the mass loss rate of the cluster.

Grillmair et al. (1995) in an analysis of star-count in the outer parts of a few galactic globular clusters found extra-cluster overdensities that they associated partly with stars stripped into the Galaxy field. Similar tidal interaction remnants around globular clusters have also been found in external galaxies: Grillmair et al. (1996) observed three clusters in M31 which exhibit departures from a King profiles. Leon et al. (1999) find tidal extensions in the outskirts of interacting binary clusters and isolated clusters in the Large Magellanic Cloud (LMC). Not surprisingly, galactic tidal forces play also an essential role in the evolution of smaller-scale galactic clusters, the open clusters: they exhibit tidal tails in their neighborhood (Odenkirchen 1998; Bergond et al. 2000).

In this work we study the 2-D structure of the tidal tails associated with 20 galactic globular clusters by using the wavelet transform to detect weak structures at large scale and filter the strong background noise for the low galactic latitude clusters. We analyze with great care the observational bias which can be very important. In Section 2 we present the observations, in Section 3 we describe the data reduction, in Section 4 we present the results with, for each globular cluster, detailed comments about related observational bias. Section 5 presents the general discussion of all results.

2. Observations

We chose to observe, for the present study, a number of clusters sharing different properties or locations in the Galaxy, with various masses and structural parameters. In order to detect the tidal extensions around globular clusters, it is necessary to have very wide field observa-
NGC 104 E12614B R 60
NGC 288 E12727R R 60
NGC 1261 ESO155 R 65
NGC 1851 E12865 R 60
NGC 1904 E12869 B 90
NGC 2298 ESO366 R 65
NGC 4372 E13090 R 60
NGC 5139 E12768 R 60
NGC 5272 E131 B
NGC 5694 ESO512 R 65
NGC 5904 SRC869 R 65
NGC 6121 E12295 R 60
NGC 6205 E1069 B
NGC 6254 ESO802 R 65
NGC 6397 E12321 R 60
NGC 6809 E12447 R 60
NGC 7492 SRC676 R 65
Pal 5 SRC869 R 65
Pal 12 ESO600 R 65

Table 1. List of observed globular clusters. About plates/films, ESO and SRC stand for the plates of the corresponding two surveys. All the other plates/films are from our observations, except the two plates E131 and E1069 which are from the POSS I.

3. Data reduction

3.1. Source extraction

Once the plates/films are digitized, the next step consists of identifying all point sources in these frames. The source extraction is performed on each frame using SExtractor (Bertin & Arnouts 1996), a software dedicated to the automatic analysis of astronomical images using a multi-threshold algorithm allowing good object deblending. The detection of the stars is done at a 3-σ level above the background. This software, which can deal with huge amount of data (up to 60,000 × 60,000 pixels) is not suited for very crowded field like the centers of the globular clusters. Since the radial surface density is so much unreliable towards the very crowded parts of these globular clusters, we just ignore it in all crowded inner areas. From the catalogues in B and R filters, produced by SExtractor for each cluster, we construct a color B and color index B − V catalogue with the instrumental magnitudes. We do not calibrate our data, except in the case of NGC 5139, since we need only relative magnitudes and colors for the purpose of establishing cluster membership. The magnitude error from the photographic plate is found to be up to 0.2 mag for the faintest stars. Typically, we get, for each field, a total number of stars from 7 × 10^4 up to 2 × 10^6 for the richest fields. We do not apply any crowding correction to our stellar counts, first, because crowding is nearly constant and weak in the outer areas (the only ones we consider) surrounding of the clusters (see also Grillmair et al. 1995), and, second, because crowding is completely dominated by the observational biases for the overdensities.

3.2. Star/Galaxy separation

In case of low fore- and background densities towards a considered globular cluster, i.e., for GCs located at
Table 2. The X, Y, Z positions are from Harris (1996) and the U, V, W velocities from Dauphole et al. (1996). † These cluster velocities are from Dinescu et al. (1997). ‡ These cluster velocities are from Scholz et al. (1998).
can differentiate present and past cluster members from the fore- and background field stars by identifying in the CMD the area occupied by cluster stars. The envelope of this area is empirically chosen so as to optimize the ratio of cluster stars to field stars in the relatively sparsely populated outer regions of each cluster.

Fig. 3. Upper right panel: color-magnitude diagram of stars in the cluster NGC 2298 (r < 0.5r_t) using instrumental magnitude. Upper left panel: color-magnitude diagram of stars in the cluster field (for clarity only 10 % of the total stars is shown). Lower panel: Signal/Noise (S/N) function for each cluster. This cumulative function reaches a maximum for a sub-area of the color-magnitude plane. Then by selecting all sub-areas with S/N values higher than this maximum, it is possible to construct the mask. In the present case, we depart slightly from Grillmair et al. (1995) procedure by selecting, for some fields, a subset of the mask, with a higher S/N value relative to the background stars (see Fig. 3 and Fig. 4). It must be a compromise between the S/N ratio and the number of stars selected, in order to get a sufficient spatial resolution which is lowered by Poissonian noise for small star counts. Given the S/N chosen, we have been able to eliminate from 50 % up to 99 % of the field stars. We show in Fig. 4 the CMD selected for the less contaminated fields.

On the CMD-selected star-count map M(x, y), we fit a background map Z(x, y), following Grillmair et al. (1995), by masking the GC (1 to 2 r_t) and using a blanking value inside, equal to the mean between 1.5 and 2.5 r_t to get a smooth background. We fit, on a 128 × 128 binned grid, a low-order bivariate polynomial surface Z(x, y), mainly first- or second-order surface, to avoid to erase some local variation:

\[
Z(x, y) = \sum_{i,j} a_{ij} x^i y^j \quad \text{with} \quad 0 \leq i, j \leq 2.
\] (4)

We subtract this background from the CMD-selected map to get a surface-density map T_r(x, y) of the overdensities that we can attribute to the tidal extension of the GC:

\[
T_r(x, y) = M(x, y) - Z(x, y)
\] (5)

after having analyzed the potential observational biases that could create the fluctuations in the star-counting analysis.

3.4. Wavelet analysis

The wavelet transform is a powerful signal processing technique which provides a decomposition of the signal into elementary local contribution labeled by a scale parameter (Grossman & Morlet 1985). They are the scalar products with a family of shifted and dilated functions of constant shape called wavelets. The data are unfolded in a space-scale representation which is invariant with respect to dilation of the signal. Such an analysis is particularly suited to study signals which exhibit space-scale discontinuities and/or hierarchical features. Its ability to detect structures at particular scales has already been used in several astrophysical problems (Gill & Henriksen 1990, Slezak et al. 1994, Cambrézy, L. 1999, Chereul et al. 1999)

3.4.1. “A trous” algorithm

We perform on the raw tidal map T_r(x, y) a wavelet analysis using the “à trous” algorithm (see Bijaoui 1991). It allows to get a discrete wavelet decomposition within a reasonable CPU time. The kernel function B_t(x, y) for the convolution is a B_t spline function. The wavelet decomposition W(i, x, y) is obtained from the following steps:

\[
c_w(x, y) = image(x, y),
\] (6)
\[ c_i(x, y) = c_{i-1} * B_s(\frac{x}{2^i}, \frac{y}{2^i}), \]  
\[ W(i, x, y) = c_i(x, y) - c_{i-1}(x, y). \]  

The last plane, called Last Smoothed Plane (LSP), is the residuals of the last convolution and not a wavelet plane, but afterwards we will abusively speak of wavelet plane for all these planes. Each plane \( W(i, x, y) \) represents the details of the image at the scale \( i \). We divide each image in 128 \times 128 bins, a process which changes the spatial resolution of each cluster according to the different sizes of the fields: typically we get star-count maps of 3′ to 16′ resolution. The spatial resolution \( \sigma_R \) for each wavelet-rebuilt cluster field can be computed, in arcmin, from the following relation: \( \sigma_R = 0.0538 \theta_{\text{field}}, \) with \( \theta_{\text{field}} \) being the total field size in arcmin. It is so far possible to do a filtering of each plane to get only the relevant wavelet component. One problem is to find the noise level for each plane. We know that the raw tidal map is blurred by the Poissonian noise of the background objects; this is especially true at low galactic latitudes. We could perform an Anscombe transformation (Murtagh et al. 1995) to transform the Poissonian noise into a Gaussian noise on each scale. Actually we choose to perform Monte-Carlo simulations, because of the varying Poissonian noise through the field, in order to follow easily the spatial variation of the rms noise at each scale. The contours for the surface density are computed to be above 3 \( \sigma \) level, with \( \sigma \) being the rms fluctuation of the selected wavelet coefficients computed in an area avoiding the central cluster.

3.4.2. Filtering of high varying density background noise

\[ W_{\text{f}}(i, x, y) = W(i, x, y) \]  
\[ \text{If } |W(i, x, y)| > \alpha \sigma_{\text{bck}}(i, x, y) \]  
\[ = 0 \]  
\[ \text{Otherwise} \]

Practically we have taken \( N=100 \). Then we fit by a low-order bivariate polynomial surface a rms noise map \( \sigma_{\text{bck}}(i, x, y) \), for each wavelet plane, to obtain an estimate of the rms fluctuation on the \( N \) realizations. This allows a good estimate of the rms noise without the need of performing a great number of simulations, which are CPU time-consuming because of the WT:

\[ W_{\text{f}}(i, x, y) = W(i, x, y) \]

\[ \text{If } |W(i, x, y)| > \alpha \sigma_{\text{bck}}(i, x, y) \]
\[ = 0 \]  
\[ \text{Otherwise} \]

In this study the coefficients are filtered at the 3-sigma level. We show the case of the globular cluster NGC 5139, located at low galactic latitude, for which we present the raw surface density map and the filtered map at different resolution (see Fig. 4 and Fig. 5). We remind that a wavelet plane \( i \) has a typical resolution of \( 0.86 \times 2^i \) pixels, which is the Gaussian-equivalent resolution of the wavelet function at the scale \( i \). We have to point out that our filtered solution is not the optimum solution (cf. Starck et al. 1997, e.g. for 1-D optimum solution) since it is only a selection of significant coefficients from the raw map. The “a trous” algorithm implemented permits a WT transform with a rate of about 2 kPixel/s/plane on a DecAlpha500 workstation.

Fig. 4. Color magnitude diagrams (left panel), using instrumental magnitude, of stars in the fields of 8 clusters with the area selected from the highest contrast between the cluster and the field. Note that the range can be different for each cluster. The right panel shows the S/N distribution \( s \) which gives the best contrast for the selection in the CMD space (see Equ. 3). For the constrast a darker color means a greater contribution from the cluster stars. In the case of NGC 288, there is no smoothing. Note that each CMD has been scaled for matching the \( s \) map.

Fig. 5. Filtered image of color-selected star-count over-densities (Log) in NGC 5139 using the Wavelet Transform (WT) (upper panel) to be compared with the raw star-count (lower panel). The upper panel displays the full resolution of 3.2′ using the whole set of wavelet planes.

In case of strong gradient density of the galactic background, the noise is varying with the location in the field. To filter properly this noise, we perform \( N \) Poissonian simulations from the fitted background star counts \( Z(x, y) \) and we take the WT of the \( N \) realizations and perform statistics on each pixel for the whole set of wavelet planes, \( W_n(i, x, y) = \text{WT}(\text{Poisson}(Z(x, y))) \) with \( n = 1, N \).

Fig. 6. Different resolutions of the tidal tail extensions towards NGC 5139 using the WT filtered planes. The spatial resolutions are 3.2′, 6.4′, 12.9′, 25.8′, 51.6′, and 103.2′ from the upper-left panel to the lower-right panel.

\[ T_f(x, y) = \sum_i W_f(i, x, y) \]  
\[ \text{with } i_1 \leq i \leq i_2 \]  
\[ \text{where } W_f \text{ is the filtered WT in case of strong background noise. The lower and upper indexes } i_1 \text{ and } i_2 \text{ constrain the} \]  

\[ \text{The IDL and C procedures for the “A trous” algorithm are available at ftp://smart.asiaa.sinica.edu.tw/pub/sle0n-wavelet.tar.gz or under request to sle0n@asiaa.sinica.edu.tw} \]
resolution of the rebuilt map by filtering the higher and/or the lower space scale wavelet planes. For the adopted binning, we find that the map with the planes 3 to 7 (LP3) gives the best compromise between the spatial resolution and the Poissonian noise of the star-counting after the filtering of the background noise. It provides, in most cases, a higher spatial resolution than in Grillmair et al. (1995), because the wavelet decomposition extract the energy only at the useful scales. We have to point out nevertheless that the wavelet basis used here is not orthogonal, mixing up slightly the scale energy on different planes, but this does not affect our rebuilt map.

4. Results

In this section we present all results related to the observations of stars surroundings of each GC. We discuss individually each cluster for the particular observational biases which could affect its results. Grillmair et al. (1995) found that the clusters in their sample with obvious tidal extensions showed a break in their surface density profiles, becoming pure power law at large radii. We try to link in a systematic way the shape of each observed tidal tail to the orbital phase of the corresponding cluster. For this we define \( Q_\alpha \) as the slope of the radial surface density between \( a \times r_t \) and \( b \times r_t \). The slope of the radial surface density is computed when the tidal tails are not dominated by the noise which would lead to a flat slope. In practice, we choose to compute the three slopes \( Q_1^t \), \( Q_3^t \), and \( Q_6^t \), and give in Table 3 their values only for clusters where the signal/noise ratio for these azimuth averaged parameters is sufficiently high. Practically, this means that we remove all clusters with \( Q_3^t \) shallower than -0.5. Whenever possible, our surface density profiles are extended inwards with the surface-brightness profiles from Trager et al. (1995), assuming a linear relation between light emission and stellar surface density through the globular cluster. Crowding and saturation problems in our plates/films make the inner parts of our density profiles highly unreliable. Consequently, the adjustment between Trager et al.’s profiles and ours is done, in the short radius range where both profiles are reliable, by adjusting a constant \( K \) in the following way:

\[
\log(\text{surface density}) = -\mu/2.5 + K
\]  

(10)

where \( \mu \) is the fitted surface brightness at \( r \) (see Trager et al., 1995). For Trager et al. (1995) profiles, only data outside the radius \( r=1' \) are shown. We point out that differences between the two profiles in the very outer parts can partly be explained by mass segregation in the cluster, unveiled by different limiting magnitudes.

It is worth mentioning that the measured slope will be flattened at small radii since the closer to the cluster the larger the crowding and since a azimuthal averaged value is more sensitive to noise at large radii. For a power law dependence, with a slope \( \alpha \), of the tidal tail surface density, the tail/noise surface density ratio scales as \( r^{-\alpha}/\sigma_{bck} \), where \( \sigma_{bck} \) is the background surface density. We choose the quantity \( Q_1^t \) — the only one we are able to determine in a large enough number of GCs — as a quantitative estimator for comparing the outer structures of these clusters. Table 3 gives, for all GCs in our sample, the dynamical and structural parameters (from GO97 and references therein) which are representative of the internal and external dynamical evolution of these globular clusters; \( t_{\text{rh}} \) is the relaxation time at the half-mass radius; \( v_{\text{evap}} \) is the destruction rate due to evaporation; the ratio \( \nu_{\text{tot}}/v_{\text{evap}} \) of the total destruction rate to the destruction rate due to evaporation illustrates the importance of the galaxy-driven evolution suffered by the clusters; \( c = \log(r_t/r_c) \) is the concentration of the cluster, where \( r_t \) and \( r_c \) are the core and tidal radii, respectively; \( M \) is the cluster mass and \( V_{HB} \) is the \( V \) magnitude of the horizontal branch stars. Given the low surface density and low S/N of some cluster tidal tails, the radial surface density profile is not shown for all the clusters.

4.1. NGC 104 \( \equiv \) 47 Tucanae

NGC 104 is at a distance of 4.1 kpc from the sun, with its horizontal branch (HB) at \( V = 14.06 \) mag. It has a tidal radius of about 55 pc with a rather high concentration \( c = \log(r_t/r_c) = 2.04 \) (see Table 3). It is one of the most massive and nearby GCs (Meylan & Mayor 1986, Meylan 1989). In their study, Odenkirchen et al. (1997) esti-

| Cluster Name | \( Q_1^t \) | \( Q_3^t \) | \( Q_6^t \) |
|-------------|---------|---------|---------|
| NGC 288     | -0.90 (0.30) | -1.56 (0.90) | -1.18 (0.18) |
| NGC 1261    | -0.96 (0.31) | 0.08 (0.20) | -0.64 (0.12) |
| NGC 1851    | -1.84 (0.20) | -0.47 (0.21) | -0.98 (0.14) |
| NGC 1904    | -1.01 (0.17) | -0.25 (0.25) | -0.65 (0.09) |
| NGC 2298    | -1.92 (0.77) | -3.41 (0.96) | -1.43 (0.39) |
| NGC 5139\† | -5.03 (0.32) |
| NGC 5272\‡ | -0.62 (0.28) | -0.40 (0.55) | -0.35 (0.24) |
| NGC 5824\‡ | -3.16 (0.64) |
| NGC 6254    | -1.91 (0.22) |
| NGC 6535    | -1.02 (0.35) | -1.69 (0.56) |
| NGC 6809    | -0.96 (0.25) |
| Average\§  | -1.24 (0.5) | -1.00 (1.3) | -0.91 (0.37) |

\† Fit between 10 et 20

\‡ Statistical dispersion (NGC 5139 not included).

\§ Statistical dispersion (NGC 5139 not included).
Table 4. Dynamical and structural parameters linked to the dynamical evolution of the globular clusters in our sample (from Gnedin & Ostriker 1997, GO97). The destruction rate \( \nu_{\text{tot}} \) includes the total destruction rate due to disk and bulge shocks from the model by Bahcall et al. (1983). The structural properties of the GCs come from the following references: (1) Pryor & Meylan (1993), (2) Hesser et al. (1986), (3) Geisler et al. (1995), (4) Meylan & Mayor (1991), (5) Webbink (1981), (6) Schweitzer et al. (1993), (7) Armandroff & Da Costa (1991), and (8) Meylan et al. (1995). All \( V_{\text{HB}} \) values are from Harris (1996). \( \dagger \) These high ratio values are due to the gravitational shocks, stronger in the Bahcall et al. (1983) model than in the Caldwell & Ostriker (1983) model (see GO97).

![Fig. 7. NGC 104 ≡ 47 Tuc. (a): Surface density plot displaying tidal tails (in Log) around NGC 104 (47 Tuc). The different arrows indicate the directions of the cluster proper motion (dotted arrow), of the galactic center (dashed arrow), and of the direction perpendicular to the galactic plane (solid arrow). The dashed circle centered on the cluster indicates its tidal radius. The horizontal double arrow stands for 150 pc. (b): IRAS 100-\( \mu \)m chart overlaid with the above tidal-tail surface density contours. The strong emission in the S-E corner is coming from the Small Magellanic Cloud (SMC).](https://reference.com/fig7.png)

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![4.2. NGC 288](https://reference.com/4.2.png)

NGC 288 is at a distance of 8.1 kpc from the sun, with its horizontal branch (HB) at \( V = 15.38 \) mag. It has a tidal radius of about 32 pc (see Table 4). Its concentration is low, with \( c = \log (r_t/r_c) = 0.96 \). It is located close to the South Galactic Pole, at 8 kpc from the Sun (Harris 1996), with a retrograde orbit (Dinescu et al. 1997). From GO97, NGC 288 is a cluster with a dynamical evo-
olution strongly driven by the galactic tidal field (see Table I). NGC 288 was already observed by Grillmair et al. (1995), who found tidal extensions on a field $200' \times 200'$ smaller than ours, but with the same spatial resolution ($16'$). In Fig. 3, the wavelet decomposition clearly reveals some wide structures missed by Grillmair et al. (1995), especially towards the south. (The arrows indicating the direction of the Galactic center in Grillmair et al. (1995) for NGC 288, NGC 362, and NGC 1904 are in error - Grillmair, private communication). No dust emission from the NGC 288, NGC 362, and NGC 1904 are in error - Grillmair et al. (1995) is surrounded by a halo of unbound stars (see Fig. 11), as previously seen by Grillmair et al. (1995), on a wider field but with a lower spatial resolution (them with $16'$, us with $6.5'$) which blurred all the small structures we observe around the cluster. We do not find evidence for a large southern tidal extension as observed by Grillmair et al. (1995). The difference here could be accounted to the lower resolution used by them, one part of this large tail could be due to the southern galaxy clusters not well separated. We point out that in their and our work we select stars below the completeness limit ($\approx 19$ mag), completeness fluctuation are another possibility to explain some differences, but not on such a large scale. The tail is oriented in the direction of the galactic center (dashed arrow) and S-E extension. The cluster position indicates that it is not suffering a strong shock, as confirmed by the ratio $\nu_{tot}/\nu_{evap} = 1.0$ from GO97, which indicates that the evolution of this cluster is mainly internally driven. Consequently, the surface density profile in the outer parts of the cluster is mainly shaped by evaporation and tidal stripping at its location in the Galaxy. Saviane et al. (1998) found a slight mass segregation in this cluster which affects the tidal tail detection by lowering the mean mass of the unbound stars (Section 5).

4.4. NGC 1851

NGC 1851 is a remote cluster at a distance of 11.7 kpc from the sun, with its horizontal branch (HB) at $V = 16.15$ mag. It has a tidal radius of about 49 pc and a very high concentration $c = \log (r_t/r_c) = 2.24$. The western part and the S-W part of NGC 1851 extension are contaminated by galaxy clusters (Abell 514 and anonymous) and by a bright star also observed by the IRAS 100-$\mu$m map (see Fig. 10). The extinction is not important towards NGC 1851, with $E(B-V) = 0.02$. Stars unbound from the cluster are likely tracing the orbital path, here these tails seem to have a preferential direction towards the galactic center (dashed arrow and S-E extension). The cluster position indicates that it is not suffering a strong shock, as confirmed by the ratio $\nu_{tot}/\nu_{evap} = 1.0$ from GO97, which indicates that the evolution of this cluster is mainly internally driven. Consequently, the surface density profile in the outer parts of the cluster is mainly shaped by evaporation and tidal stripping at its location in the Galaxy. Saviane et al. (1998) found a slight mass segregation in this cluster which affects the tidal tail detection by lowering the mean mass of the unbound stars (Section 5).

4.5. NGC 1904 $\equiv$ M79

NGC 1904 is a remote cluster located at a distance of 12.2 kpc from the sun, with its horizontal branch (HB) at $V = 16.15$ mag. It has a tidal radius of about 32 pc and a concentration $c = \log (r_t/r_c) = 1.72$. NGC 1904 is surrounded by a halo of unbound stars (see Fig. 11), as previously seen by Grillmair et al. (1995), on a wider field but with a lower spatial resolution (them with $16'$, us with $6.5'$) which blurred all the small structures we observe around the cluster. We do not find evidence for a large southern tidal extension as observed by Grillmair et al. (1995). The difference here could be accounted to the lower resolution used by them, one part of this large tail could be due to the southern galaxy clusters not well separated. We point out that in their and our work we select stars below the completeness limit ($\approx 19$ mag), completeness fluctuation are another possibility to explain some differences, but not on such a large scale. The tail is oriented in the direction of the galactic center (dashed arrow). As in the case of NGC 288, the tidal radius determination may be overestimated because of the presence of galaxy clusters close to NGC 1904. Nevertheless, the tidal tails of this cluster do not appear to be correlated with the distribution of the extra-galactic objects. The dust extinction is low towards this cluster ($E(B-V) = 0.01$) and the fluctuations of the dust emission are low as...
Fig. 8. NGC 288. (a): Surface density plot displaying tidal tails (in Log) around NGC 288. The different arrows indicate the directions of the cluster proper motion (dotted arrow), of the galactic center (dashed arrow), and of the direction perpendicular to the galactic plane (solid arrow). The dashed circle centered on the cluster indicates its tidal radius. The horizontal double arrow scale stands for 200 pc. (b): Tidal-tail density overlaid with the surface density contours of galaxies (>3-σ) at the same resolution. (c): Radial surface density profile with the power-law fit to our data in the external parts, while the inner surface density profile comes from the data (diamond) by Trager et al. (1995), shifted vertically to fit our star count data. The vertical arrow indicates the tidal radius. (d): Overdensities of galaxy counts overlaid with the positions of the Abell clusters (triangle) known in the same field.

Fig. 9. NGC 1261. (a): Surface density plot displaying tidal tails (in Log) around NGC 1261. The different arrows indicate the direction of the galactic center (dashed arrow) and of the direction perpendicular to the galactic plane (solid arrow). The dashed circle centered on the cluster indicates its tidal radius. The horizontal double arrow scale stands for 100 pc. (b): Tidal-tail density overlaid with the surface density contours of galaxies (>3-σ) at the same resolution. (c): Radial surface density profile with the power-law fit to our data in the external parts, while the inner surface density profile comes from the data (diamond) by Trager et al. (1995), shifted vertically to fit our star count data. The vertical arrow indicates the tidal radius. (d): Overdensities of galaxy counts; there is no Abell galaxy cluster in this field.

Fig. 10. NGC 1851. (a): Surface density plot displaying tidal tails (in Log) around NGC 1851. The different arrows indicate the direction of the galactic center (dashed arrow) and of the direction perpendicular to the galactic plane (solid arrow). The dashed circle centered on the cluster indicates its tidal radius. The horizontal double arrow scale stands for 100 pc. (b): Tidal-tail density overlaid with the surface density contours of galaxies (>3-σ) at the same resolution. (c): IRAS 100-µm chart overlaid with the above tidal-tail surface density contours. (d): Overdensities of galaxy counts overlaid with the Abell clusters (triangle) detected in the same field. (e): Radial surface density profile with the power-law fit to our data in the external parts, while the inner surface density profile comes from the data (diamond) by Trager et al. (1995), shifted vertically to fit our star count data. The vertical arrow indicates the tidal radius.

Traced by the IRAS 100-µm map. Because of the short relaxation time of NGC 1904 ($t_{rh} = 8.8 \times 10^8$ yr), the mass segregation should affect as well the stellar populations in the tidal tails. Since, following GO97, $v_\text{tot} = 30$% higher than $v_{\text{evap}}$, this may indicate a slight influence of the galaxy on this cluster.

4.6. NGC 2298

NGC 2298 is a remote cluster located at a distance of 10.4 kpc from the sun, with its horizontal branch (HB) at $V = 16.11$ mag. It has a tidal radius of about 19 pc and a concentration $c = \log (r_t/r_c) = 1.40$. There are background fluctuations owing to the dust along the line of sight, as clearly traced by the IRAS 100-µm map (see Fig. 12). We perform a quite high tail/background S/N CMD selection because of the high background density (see Fig. 3), but there is still a bias because of the dust extinction, as seen in Fig. 4. There is a southern extension towards the galactic center (dashed arrow) which is interrupted by dust absorption. Some parts of the Eastern extension located at $(x = -50, y = -10)$ of the tidal tails may be questionable, because of the stronger dust presence, nevertheless the lower absorption can hardly explain all these overdensities, since their distribution does not follow the minimum IRAS 100-µm emission map. Clearly, the overdensity at $(x = 60, y = 60)$ is associated with a low IRAS emission area. Given the position and the distance of NGC 2298 from the galactic center (15.1 kpc), the southern extension is likely tracing its orbital path and not the result of gravitational shock, as indicated by the ratio $v_\text{tot}/v_{\text{evap}} = 1.0$ from GO97. The low value $Q_\text{K}= -0.25$, likely due to the small extensions in the outer parts, is questionable.

Fig. 12. NGC 2298. (a): Surface density plot displaying tidal tails (in Log) around NGC 2298. The different arrows indicate the direction of the galactic center (dashed arrow) and of the direction perpendicular to the galactic plane (solid arrow). The dashed circle centered on the cluster indicates its tidal radius. The horizontal double arrow scale stands for 100 pc. (b): IRAS 100-µm chart overlaid with the above tidal-tail surface density contours.

4.7. NGC 4372

NGC 4372 is a nearby globular cluster located at a distance of 4.6 kpc from the sun, with its horizontal branch (HB) at $V = 15.30$ mag. It has a tidal radius of about 52 pc and a concentration $c = \log (r_t/r_c) = 1.30$. The pre-
Fig. 11. NGC 1904. (a): Surface density plot displaying tidal tails (in Log) around NGC 1904. The different arrows indicate the direction of the galactic center (dashed arrow) and of the direction perpendicular to the galactic plane (solid arrow). The dashed circle centered on the cluster indicates its tidal radius. The horizontal double arrow scale stands for 100 pc. (b): Tidal-tail density overlaid with the surface density contours of galaxies (>3-σ) at the same resolution. (c): Radial surface density profile with the power-law fit to our data in the external parts, while the inner surface density profile comes from the data (diamond) by Trager et al. (1995), shifted vertically to fit our star count data. The vertical arrow indicates the tidal radius. (d): Overdensities of galaxy counts; there is no Abell galaxy cluster in this field.

sentation of the detection of the overdensities around this cluster illustrates the dramatic influence of varying dust extinction (see Fig. 13). Strangely enough, the very elongated dust filament observed in the IRAS 100-μm map ends very close to the cluster: this may suggest an interaction of the cluster with the interstellar medium currently at play. Following GO97 (see Table 4), this cluster has an evolution strongly driven by the galaxy (vtot/vevap = 3.8).

Fig. 13. NGC 4372. IRAS 100-μm map overlaid with the contours of the overdensities in star-counts, which are completely disturbed by the dust extinction, particularly along the elongated dust filament. The different arrows indicate the direction of the galactic center (dashed arrow) and of the direction perpendicular to the galactic plane (solid arrow). The dashed circle centered on the cluster indicates its tidal radius. The horizontal double arrow scale stands for 100 pc.

4.8. NGC 5139, ω Cen

NGC 5139, the most massive galactic globular cluster (Meylan 1987, Meylan et al. 1995, Merritt et al. 1997), currently crossing the disk plane, is a nearby globular cluster located at a distance of 5.0 kpc from the sun, with its horizontal branch (HB) at V = 14.53 mag. It has a tidal radius of about 65 pc and a concentration c = log (rt/rc) = 1.24. Its relative proximity allows to reach the main sequence for the star count selection.

Given the very good tail/background S/N ratio, we perform an absolute calibration of the photometry using the data from Cannon & Stobie (1973) and Alcaino & Liller (1987) with an error which is still about σ = 0.2 mag. Although obvious biases by dust absorption affect the star counts, as seen, e.g., at the positions (x = 50, y = −25) and (x = −50, y = −70) on the IRAS 100-μm map (Fig. 14), there are two large and significant tidal tails: NGC 5139 is releasing currently some large amounts of stars. The tidal tail extensions are perpendicular to the galactic plane (see Fig. 14), which is a clear sign of disk-shocking, as observed in our numerical simulations (CLM99). By considering star-counts with magnitude B < 19 (the completeness limit), we found about 7000 ±600 stars outside one tidal radius, in the 4° × 4° field. This magnitude corresponds to a 0.63 M⊙ star at a distance of 5 kpc. Assuming the same mass function in the cluster and in the tidal extensions, because of its large relaxation time, we estimate a total of 1.9 10⁶ M⊙ for the escaped stars, with the assumption of a Salpeter law (α = −2.35) mass function for the stars down to 0.1 M⊙. Thus the tidal tails represent about 0.6 % of the cluster mass for total cluster mass of about 5.1 10⁶ M⊙. This is consistent with the numerical simulations (CLM99, Johnston et al. 1998) given the high uncertainties on the mass function, the photometric calibration, the mass-luminosity relation used (see e.g., Saviane et al. 1998), and the possible steeper mass function in the tidal tails, as discussed in Section 5 for a slope α = −2.8. We point out that a steeper mass function has been observed in the halo of NGC 5139 (Anderson, 1998).

The Q² parameter value and the position of the cluster in the galaxy indicate that NGC 5139 is presently experiencing a disk shocking, with an important mass loss of stars, whose presence is clearly observed in the immediate neighborhood of the cluster. The observed proper motion of NGC 5139 indicates that this cluster is in the early phases of its disk crossing. This confirms the high value of the ratio vtot/vevap = 9.4 estimated by GO97. In the case of NGC 5139, the disk-shocking consequences are combined with the bulge-shocking ones, since the cluster orbit goes as close as 1.8 kpc from the galactic center (Dauphole et al. 1996).

We choose to present here the same wavelet planes that those for the other clusters, but given the high density — significance – of NGC 5139 tidal tails, we illustrate, in Fig. 13, the different spatial resolutions for ω Cen after filtering of the background noise. It is worth mentioning that, because of the internal rotation of this cluster (Meylan & Mayor 1986, Merritt, Meylan & Mayor 1997), the global mass loss rate is enhanced by a factor of 2 with respect to the N-body simulations (CLM99) and Fokker-Planck estimates (Longaretti & Lagoute 1996). In the discussion we consider the effect of the mass segregation on the mass loss derivation.

4.9. NGC 5272 ≡ M3

NGC 5272 is a globular cluster located at a distance of 9.7 kpc from the sun, with its horizontal branch (HB) at V = 15.65 mag. It has a tidal radius of about 105 pc and a concentration c = log (rt/rc) = 1.85. The cluster is near...
the edge of the plate, preventing the study of its Eastern side (see Fig. 13). The field is polluted only by 2 small galaxy clusters, viz. Abell 1781 and Abell 1769, the former being detected only at 2.5-σ level. Unfortunately, a defect on the plate E131 (POSS) have blurred the extragalactic object detection (peak at x = 120, y = –20). We emphasize that point-source detection with SExtractor is less affected by this defect. There is no anticorrelation at all between the tidal tails and the dust emission, as we checked with the IRAS 100-μm map, which is at a low level (E(B − V) = 0.01). The extension at (x = –30, y = –50), towards the galactic center (dashed arrow), is the more reliable. Thus from the low value of the slope $Q_{1}^B = -0.35$, we can infer that the field pollution bias must be quite strong, providing a rather constant radial surface density. The comparison with the data from Trager et al. (1995), which obtained star-count values smaller than our density, shows that the mass segregation should not affect strongly the mass function of the unbound stars. Gunn & Griffin (1979) found some weak rotation in this globular cluster which should slightly enhance the mass loss rate by a factor 1.1-1.2 (Longaretti & Lagoute 1996). There is no apparent correlation between the tidal tail direction and the proper motion of the cluster (dotted arrow).

4.10. NGC 5694

NGC 5694 is a very remote globular cluster located at a distance of 33 kpc from the sun, with its horizontal branch (HB) at $V = 18.50$ mag, which is a strong limitation for star counts. Given its large distance from the galactic center, namely 27.5 kpc, this cluster is not expected to suffer strong gravitational shocks ($\nu_{\text{tot}}/\nu_{\text{evap}} = 1.0$, GO97). It has a tidal radius of about 41 pc and a concentration $c = \log (r_t/r_c) = 1.84$. We select the stars on the giant branch only, with a higher tail/background S/N ratio in order to avoid as much as possible the galaxies which are the strongest bias in this field (see Fig. 13). The lower dust extinction, mapped through IRAS 100-μm emission, could induce an artificial extension in the S-W part of the cluster, at the position (x = 20, y = –15). But the huge extension in the S-E part can be attributed to extra-tidal material, with high confidence since it is correlated with higher dust extinction and there is only one small galaxy cluster at the position (x = –20, y = –3). It must be stars tidally stripped from the cluster, material which is now trailing/leading along the orbit of the cluster. As in the other clusters, it is aligned towards the galactic center direction (dashed arrow), but it might also be a projection effect of its orbital plane with the galactic center direction. The size of this extension is about 300 pc in the sky and is probably even much larger because of the shallow photometry available on this distant cluster.

4.11. NGC 5824

NGC 5824 is a very remote globular cluster located at a distance of 32.2 kpc from the sun, with its horizontal branch (HB) at $V = 18.60$ mag, which is a strong limitation for star counts. At a large distance from the galactic center, namely 26 kpc, this cluster is not expected to suffer strong gravitational shocks ($\nu_{\text{tot}}/\nu_{\text{evap}} = 1.6$, GO97). It has a tidal radius of about 147 pc and a concentration $c = \log (r_t/r_c) = 2.45$. Because of a low tail/background S/N ratio, a consequence of the faint $V_{\text{HB}}$ magnitude, the over-density map around NGC 5824 appears to be very noisy (Fig. 17). Grillmair et al. (1995) find around this cluster more extended structures, aligned with the N-S direction, than we do in the same field: this may be partly due to our rather shallow photographic films. There are some strong biases due to dust extinction as it can be seen on Fig. 13 at the position (x = –20, y = –20) and due also to some galaxies spread mainly over the Southern part. GO97 indicate that NGC 5824 should experience important interactions with the tidal galactic field, a prediction we are not able to confirm because of the tangled observational biases. But it appears that a preferential direction of the cluster extension could be perpendicular to the galactic plane (solid arrow), either due to a disk shocking or tracking the orbital motion of the cluster. Nevertheless a bulge shocking effect cannot be ruled out in the case of a very eccentric orbit.

4.12. NGC 5904 ≡ M5

NGC 5904 is a globular cluster located at a distance of 7 kpc from the sun, with its horizontal branch (HB) at $V = 15.06$ mag. It has a tidal radius of about 66 pc and a concentration $c = \log (r_t/r_c) = 1.87$. We present only the S-E part of the tidal extensions (Fig. 13) because of its position on the plate. No bias due to dust is reported towards this field (E(B − V) = 0.03). The presence on a galaxy...
Fig. 15. NGC 5272. (a): Surface density plot displaying tidal tails (in Log) around NGC 5272. The different arrows indicate the directions of the cluster proper motion (dotted arrow), of the galactic center (dashed arrow), and of the direction perpendicular to the galactic plane (solid arrow). The dashed circle centered on the cluster indicates its tidal radius. The horizontal double arrow scale stands for 200 pc. (b): Above tidal-tail density overlaid with the surface density contours of galaxies (>3-σ) at the same resolution. (c): Radial surface density profile with the power-law fit to our data in the external parts, while the inner surface density profile comes from the data (diamond) by Trager et al. (1995), shifted vertically to fit our star count data. The vertical arrow indicates the tidal radius. (d): Overdensities of galaxy counts overlaid with the Abell clusters (triangle) detected in the same field. The extended structure is due to spurious detections because of a defect on the plate (see text).

Fig. 16. NGC 5694. (a): Surface density plot displaying tidal tails (in Log) around NGC 5694. The different arrows indicate the direction of the galactic center (dashed arrow) and of the direction perpendicular to the galactic plane (solid arrow). The dashed circle centered on the cluster indicates its tidal radius. The horizontal double arrow scale stands for 200 pc. (b): Tidal-tail density overlaid with the surface density contours of galaxies (>3-σ) at the same resolution. (c): IRAS 100-µm chart overlaid with the above tidal-tail surface density contours. (d): Overdensities of galaxy counts; there is no Abell galaxy cluster in this field.

Fig. 17. NGC 5824. (a): Surface density plot displaying tidal tails (in Log) around NGC 5824. The different arrows indicate the direction of the galactic center (dashed arrow) and of the direction perpendicular to the galactic plane (solid arrow). The dashed circle centered on the cluster indicates its tidal radius. The horizontal double arrow scale stands for 400 pc. (b): Tidal-tail density overlaid with the surface density contours of galaxies (>3-σ) at the same resolution. (c): IRAS 100-µm chart overlaid with the above tidal-tail surface density contours. (d): Overdensities of galaxy counts overlaid with the Abell cluster (triangle) detected in the same field.

Cluster close to the tidal radius of the cluster enhances artificially and locally the tidal tail pointing towards the galactic center (dashed arrow) and the direction perpendicular to the galactic plane (solid arrow). Nevertheless, it is obvious that an extension is present towards this direction, since the galaxy cluster size is significantly smaller than the size of the globular cluster extension, as shown on Fig. [3] with the same resolution used for the star and galaxy surface densities. Lehmann & Scholz (1996) found already indication of tidal tail around this cluster from its surface brightness profile which deparnts from a King profile; this may be explained as well by the galaxy cluster near the tidal radius. From Odenkirchen et al. (1997), NGC 5904 is just beginning its crossing through the disk and towards the galactic center. Consequently, we could observe the first effect of the gravitational shocking on this cluster, with the tail aligned towards the tidal directions (see CLM99) after being compressed during the crossing. Indeed the momentum transfer to the cluster stars is in the Z direction during the disk shocking. From GO97, NGC 5904 suffers strong interactions with the galaxy, with $\nu_{\text{tot}}/\nu_{\text{evap}} = 26$, a high value due to the use of the Bahcall et al. (1983) galactic model which enhances the gravitational shocks because of its nuclear component and the form of the disk potential which does not vanishes at the center as it is the case for the model from Ostriker & Caldwell (1983).

4.13. NGC 6205 ≡ M13

NGC 6205 is a globular cluster located at a distance of 6.8 kpc from the sun, with its horizontal branch (HB) at $V = 14.90$ mag. It has a tidal radius of about 56 pc and a concentration $c = \log (r_1/r_c) = 1.49$. The bias towards NGC 6205 are not strong as shown by the weak IRAS 100-µm flux and the relatively high tail/background S/N ratio in the CMD. Given the position of the cluster on the survey plates, we extract a field of 90' in size. There is no strong bulk of tidal stars (see Fig. [19]) due to any shock and the field is too small to detect any large scale structure corresponding to the orbital path. An extension can be seen towards the galactic center (dashed arrow) at the position $(x = -10, y = -25)$, although located inside the tidal radius, which highlights the limitation of an azimuthally averaged radial surface density. This extension is not correlated with the proper motion. We note that an extended default on the plate center worsens the cluster/background star separation.

Fig. 19. NGC6205. Surface density plot displaying tidal tails (in Log) around NGC 6205. The different arrows indicate the directions of the cluster proper motion (dotted arrow), of the galactic center (dashed arrow), and of the direction perpendicular to the galactic plane (solid arrow). The dashed circle centered on the cluster indicates its tidal radius. The horizontal double arrow scale stands for 100 pc.
**Fig. 18.** NGC 5904 \( \equiv \) M5. (a): Surface density plot displaying tidal tails (in Log) around NGC 5904. The different arrows indicate the directions of the cluster proper motion (dotted arrow), of the galactic center (dashed arrow), and of the direction perpendicular to the galactic plane (solid arrow). The dashed circle centered on the cluster indicates its tidal radius. The horizontal double arrow scale stands for 100 pc. (b): Tidal-tail density overlaid with the surface density contours of galaxies (>3-\( \sigma \)) at the same resolution. (c): Overdensities of galaxy counts overlaid with the Abell cluster (triangle) detected in the same field.

### 4.14. NGC 6254 \( \equiv \) M10

NGC 6254 is a nearby globular cluster located at a distance of 4.1 kpc from the sun, with its horizontal branch (HB) at \( V = 14.65 \text{ mag} \). It has a tidal radius of about 26 pc and a concentration \( c = \log \left( r_t/r_c \right) = 1.40 \). This cluster is a striking case because of a strong gradient in the dust extinction as seen on Fig. 21, overlaid with the IRAS 100-\( \mu \text{m} \) map. The southern extension anticorrelates quite well with the dust emission which is the sign of a possible bias. An obvious decrease of the stellar surface density is correlated with the dust emission at the position \((x = -40, y = -30)\). Nevertheless the inner NE-SW and the northern extensions are not anticorrelated with the dust emission. The second break at \( \log(r) \simeq 1.6 \), apart from the one around the tidal radius, in the radial density profile (see Fig. 21c) must correspond to a very recent disk-shocking, with the diffusing stars (cf. CLM99) still close to the cluster. This conclusion is strengthened by the proper motion of the cluster whose direction (dotted arrow) is opposite to the disk direction (solid arrow); Odenkirchen et al. (1998) indicate that NGC 6254 suffered its last disk crossing about 20 Myr ago. Considering the northern extension as a genuine tidal tail made of stars from NGC 6254, we can give a lower limit for the diffusion velocity, which is a projected expansion velocity of the tidal material in the cluster reference frame: at a distance of 4.1 kpc, for a projected distance of 150 pc, we obtain about 7 \( \text{km s}^{-1} \) as a lower limit of the diffusion velocity. We note that the velocity dispersion of stars in NGC 6254 is similar, with \( \sigma_0 = 6.6 \text{ km s}^{-1} \) (Pryor & Meylan 1993). This velocity diffusion probes the differential diffusion of stars released in the Galaxy along with the global dynamical friction of the cluster which is not felt by the unbound stars. Actually this diffusion velocity is surprisingly high compared to the dispersion velocity, where we would expect low velocity dispersion for the unbound stars: a misclassification of these clumps as genuine cluster stars or an underestimation of the last crossing time cannot be ruled out. Given the quite short relaxation time \( t_{rh} = 7.6 \times 10^8 \text{ yr} \), the mass segregation must be present in this cluster, even though Hurley et al. (1989) did not find any evidence. Such a mass segregation must lead to a steep mass function in the tidal tails.

### 4.15. NGC 6397

NGC 6397 is a very nearby globular cluster located at a distance of 2.2 kpc from the sun, with its horizontal branch (HB) at \( V = 12.87 \text{ mag} \). It has a tidal radius of about 66 pc and a concentration \( c = \log \left( r_t/r_c \right) = 2.50 \). It is the only post core-collapsed cluster in our sample, although NGC 1851 and NGC 5824 have also rather large concentrations. This is the second example, with NGC 4372, of overdensities strongly biased by dust extinction fluctuations as it can be seen in Fig. 21. All the overdensities found in the northern and eastern parts cannot be disentangled from dust extinction. Only the S-E extension, at the position \((x = -100, y = -100)\), could be a genuine tidal tail, but with a somewhat low confidence in spite of the fact that these star counts are more than 3 \( \sigma \) above the background because the dust extinction fluctuations in this field are quite high \( \left( \sigma^2(S_{100}) \simeq 5_{100} \simeq 20 \text{ MJy/sr} \right) \). Nevertheless, we emphasize that this extension is perpendicular to the plane (solid arrow) as expected for disk shocking (CLM99), thanks to the momentum transfer in the Z direction. During the disk crossing the gained acceleration for the cluster stars is directed towards the cluster equatorial plane parallel to the galactic plane. Then the energy gained is released in this direction, perpendicular to the galactic plane. The mass segregation found by Mould et al. (1996) in this cluster will affect the mass function of the tidal tails. A weak rotation of NGC 6397 has been found (Meylan & Mayor 1991) which should enhance the mass loss rate by about 20 \%, using Fig. 7 of Longaretti & Lagoute (1996).

### 4.16. NGC 6535

NGC 6535 is a globular cluster located at a distance of 6.6 kpc from the sun, with its horizontal branch (HB) at \( V = 15.73 \text{ mag} \). It has a tidal radius of about 17 pc and a concentration \( c = \log \left( r_t/r_c \right) = 1.30 \). In spite of the high tail/background S/N color selection on the CMD in order to avoid the high background density, the clus-
Fig. 20. NGC 6254. (a): Surface density plot displaying tidal tails (in Log) around NGC 6254. The different arrows indicate the directions of the cluster proper motion (dotted arrow), of the galactic center (dashed arrow), and of the direction perpendicular to the galactic plane (solid arrow). The dashed circle centered on the cluster indicates its tidal radius. The horizontal double arrow scale stands for 100 pc. (b): IRAS 100-µm chart overlaid with the above tidal-tail surface density contours. Lower-right panel (c): Radial surface density profile with the power-law fit to our data in the external parts, while the inner surface density profile comes from the data (diamond) by Trager et al. (1995), shifted vertically to fit our star count data. The vertical arrow indicates the tidal radius.

NGC 6809 is a globular cluster located at a distance of 5.1 kpc from the sun, with its horizontal branch (HB) at V = 14.40 mag. It has a tidal radius of about 23 pc and a concentration $c = \log (r_t/r_c) = 0.76$. The overdensities (see Fig. 22) are strongly anticorrelated with the dust emission traced by the IRAS 100-µm map, e.g. at the position (x = 0, y = –20). As indicated by GO97, the evolution of this cluster is influenced by the galactic potential ($\nu_{\text{tot}}/\nu_{\text{evap}} = 1.4$). Currently, NGC 6535 is experiencing a strong bulge shocking and disk shocking as indicated by the correlation of the tail with the disk/bulge direction (solid and dashed arrows, respectively) and confirmed by its location in the galaxy, viz. 1.2 kpc above the plane and 4 kpc from the galactic center (Harris 1996).

NGC 7492 is a remote globular cluster located at a distance of 21.8 kpc from the sun, with its horizontal branch (HB) at V = 17.63 mag. It has a tidal radius of about 107 pc and a concentration $c = \log (r_t/r_c) = 0.74$. It is one of the most remote cluster with measured proper motions (Schweitzer et al. 1993, Scholz et al. 1998). The tidal radius could be lower than previously measured, down to 7’, in agreement with its orbit (Scholz et al. 1998). In Fig. 23 we present the overdensities, which are strongly biased by the background galaxy clusters present in the field. Because of the unreliable star/galaxy separation above $R \approx 18$, the confusion is quite strong for this remote and faint cluster. As pointed out already by Scholz et al. (1998), the galaxy cluster Abell 2050 could be responsible for the previous (commonly adopted) overestimate of the tidal radius. The dust extinction is very weak in this field ($E(B-V) = 0.03$), and do not exhibit any anticorrelation with the overdensities, as checked on the IRAS 100-µm map. The background galaxy distribution and the large distance to this cluster make difficult any conclusion on the genuine location, if any, of stars stripped from the cluster.

NGC 7492 is a remote globular cluster located at a distance of 24.3 kpc from the sun, with its horizontal branch (HB) at V = 17.63 mag. It has a tidal radius of about 62 pc and a concentration $c = \log (r_t/r_c) = 1.0$. There is no dust emission towards this field and the background galaxy clusters are located far from the cluster, as indicated in Fig. 24. Obviously, the overdensity at the position (x = 18, y = 25) is associated with the galaxy cluster Abell 2533. Because of the low mass of this cluster, GO97 find a fast evolution in the Galaxy field, with $\nu_{\text{tot}}/\nu_{\text{evap}} = 77.8$, compared to its intrinsic evolution. Clearly, a tiny extension is visible, pointing towards the galactic center (dashed arrow). This lack of tidal extension is not in contradiction with the conclusion drawn by GO97, given its current location far from the center of the Galaxy (23.5 kpc). A higher tail/background S/N ratio selection, using high-quality CCD data, may allow the detection of very low surface density extension related to tidal tails extending away from NGC 7492.

Palomar 5 is a remote globular cluster located at a distance of 21.8 kpc from the sun, with its horizontal branch (HB) at V = 17.63 mag. It has a tidal radius of about 107 pc and a concentration $c = \log (r_t/r_c) = 0.74$. It is one of the most remote cluster with measured proper motions (Schweitzer et al. 1993, Scholz et al. 1998). The tidal radius could be lower than previously measured, down to 7’, in agreement with its orbit (Scholz et al. 1998). In Fig. 23 we present the overdensities, which are strongly biased by the background galaxy clusters present in the field. Because of the unreliable star/galaxy separation above $R \approx 18$, the confusion is quite strong for this remote and faint cluster. As pointed out already by Scholz et al. (1998), the galaxy cluster Abell 2050 could be responsible for the previous (commonly adopted) overestimate of the tidal radius. The dust extinction is very weak in this field ($E(B-V) = 0.03$), and do not exhibit any anticorrelation with the overdensities, as checked on the IRAS 100-µm map. The background galaxy distribution and the large distance to this cluster make difficult any conclusion on the genuine location, if any, of stars stripped from the cluster.

Palomar 12 is a remote globular cluster located at a distance of 17.8 kpc from the sun, with its horizontal branch (HB) at V = 17.63 mag. It has a tidal radius of about 49 pc and a concentration $c = \log (r_t/r_c) = 0.90$. The dust extinction is very low ($E(B-V) = 0.02$), but the contamination by background galaxy clusters is very important (see Fig. 24), although only two Abell galaxy clusters are reported in this field. The N-S oriented very long tail is contaminated by some galaxies as shown at position (x =
Fig. 22. NGC 6535. (a): Surface density plot displaying tidal tails (in Log) around NGC 6535. The different arrows indicate the direction of the galactic center (dashed arrow) and of the direction perpendicular to the galactic plane (solid arrow). The dashed circle centered on the cluster indicates its tidal radius. The horizontal double arrow scale stands for 50 pc. (b): IRAS 100-µm chart overlaid with the above tidal-tail surface density contours. (c): Radial surface density profile with the power-law fit to our data in the external parts, while the inner surface density profile comes from the data (diamond) by Trager et al. (1995), shifted vertically to fit our star count data. The vertical arrow indicates the tidal radius.

Fig. 23. NGC 6809 ≡ M55. (a): Surface density plot displaying tidal tails (in Log) around NGC 6809. The different arrows indicate the direction of the galactic center (dashed arrow) and of the direction perpendicular to the galactic plane (solid arrow). The dashed circle centered on the cluster indicates its tidal radius. The horizontal double arrow scale stands for 100 pc. (b): IRAS 100-µm chart overlaid with the above tidal-tail surface density contours. (c): Radial surface density profile with the power-law fit to our data in the external parts, while the inner surface density profile comes from the data (diamond) by Trager et al. (1995), shifted vertically to fit our star count data. The vertical arrow indicates the tidal radius.

Fig. 24. NGC7492. (a): Surface density plot displaying tidal tails (in Log) around NGC 7492. The different arrows indicate the direction of the galactic center (dashed arrow) and of the direction perpendicular to the galactic plane (solid arrow). The dashed circle centered on the cluster indicates its tidal radius. The horizontal double arrow scale stands for 100 pc. (b): Tidal-tail density overlaid with the surface density contours of galaxies (>3-σ) at the same resolution. (c): Overdensities of galaxy counts overlaid with the Abell cluster (triangle) detected in the same field.

15, y = 30) in Fig. 23. Nevertheless this tail is a genuine feature made of stars tidally stripped, as shown by the distribution of the galaxies as the same resolution. The western and eastern overdensities are related mainly to galaxies. A higher tail/background S/N CMD selection confirmed the Pal 12 membership of the top and bottom clumps at positions (x = 0, y = ±60). To get an estimate of the time of the last, if any, gravitational shock on this cluster, we assume that these two latter star clumps are remains of the last shock. Adopting a diffusion velocity for the tidal stars equal to 1 km s⁻¹, similar to the velocity dispersion (Djorgovski & Meylan 1994) of such a low mass cluster (2 x 10⁴ M☉) and assuming the distance in projection between the clumps and the cluster to be 350 pc, we estimate 350 Myr as the time since the last shock. This is a lower limit because of the projection effect and the limited field. Contrary to most other tidal tail directions, the extension is perpendicular to the galactic center direction (dashed arrow) and is in a plane parallel to the galactic disk.

5. Discussion

Fig. 27. The slope values Q1³ (between r₁ and 3r₁) versus Q6³ (between 3r₁ and 6r₁) in clusters with wide enough field. The dotted line stands for Q1³ = Q6³.

The detection of stars tidally stripped from globular clusters emphasizes strongly the importance of the interactions of these stellar systems with the Galaxy. In the light of the possible biases present in the above observed fields, it is possible to give an estimate of the physical status of the clusters relative to the gravitational shocks they suffer in the Galaxy (see Table 5). In the case of a cluster experiencing disk-shocking only, it will be first compressed in the direction perpendicular to the galactic plane, during the short time of the crossing; then the tidally released stars form tails perpendicular to the galactic plane (see, e.g., NGC 5139). In the case of a cluster experiencing bulge-shocking only, i.e., not too far from the Galaxy center, the tails are elongated mainly along the galactic density gradient (spherical symmetry) and one can expect a correlation between the tidal tail direction and the galactic center. This is true also for the more general case of galaxy-shocking, when bulge- and disk-shocking are both at play, i.e., when the cluster is close to the galactic center. If the cluster has not experienced for a long time a gravitational shock, its tidal tails are on a large scale oriented along its orbit. However Grillmair (1992) showed using N-body simulations, without any disk potential, that strong “bars” orthogonal to the orbital path will develop naturally near the apogalactica of the cluster’s orbit. In Table 3 we, tentatively, give the processes at play for creating the recent mass loss in the clusters: it is based on tidal tails shapes, but, as well, on their positions in the Galaxy and their orbit and proper motions, when they are available. It explains the discrepancy between some tidal tail orientation and the type of physical process. We point out that the projection effect must be important in some case (e.g. NGC 288). It has to be noted that a combination of disk- and bulge-shocking are expected to confuse the above simplified scenario (e.g. NGC 6535).
The case of NGC 5904 is interesting since its proper motion is known: the small tidal extension observed is perfectly aligned towards the galactic center and the direction perpendicular to the galactic plane and not with its motion along its orbit. Given its position in the Galaxy, this cluster is probably suffering a weak disk and bulge shocking.

In Fig. 27 we show the slope values $Q_1^3$ (between $r_1$ and $3r_1$) versus $Q_3^6$ (between $3r_3$ and $6r_3$) for the few clusters where it is possible to measure these two parameters. We emphasize that these slope values are probably overestimated, especially for $Q_1^3$, because of central crowding. As found in dynamical simulations by Johnston et al. (1998) and in other observations by Grillmair et al. (1998) on different radius ranges, the mean slope value for $Q_1^3$ is $-0.91 \pm 0.24$. The coefficient $Q_3^6$ presents a strong scatter (1.69) around its mean value equal to $-1.0$. Its determination is difficult because the stars no more bound to the cluster have a very low density in the outer parts where the noise dominates (see, e.g., NGC 2298). The quantity $Q_1^3$ must be a reliable indicator of the recent mass loss from the cluster, with a steep slope for the cluster suffering shocks. Then the diffusion of the heated stars will flatten the surface density profile.

In Fig. 28, we present, from our N-body simulations (CLM99), the variation with time of the surface density slope fitted on a power law for two different ranges of radii. It is remarkable to note the strong variation of the slopes during the crossing of the galactic plane. Moreover there is a delay between the variation of the $\alpha(30-40pc)$ slope and $\alpha(40-50pc)$ slope. Here the dumping frequency of the simulations is too low to allow any estimate of the diffusion velocity of the bulk of stars stripped during the crossing. It appears nevertheless to be lower than the velocity dispersion of the simulated globular cluster ($\sim 8 \text{ km s}^{-1}$).

We may link the case of NGC 6254 (see Fig. 20) to the surface density profile computed from our N-body simulations (CLM99) before and after the crossing and displayed in Fig. 29. Clearly the second break, at a radius $r > r_1$, in the observed cluster density profile (log($r$) $\sim 1.6$) and simulated cluster density profile (log($r$) $\sim 1.9$) indicates that disk shocking is currently at play on NGC 6254 and the halo of unbound stars has not yet diffused outwards. Even if other mechanisms could produce such break (e.g. “bars” at the apogalactica radius) we note that this NGC 6254 is currently just 1.6 kpc above the galactic plane.

The variations of the $Q_1^3$ coefficient between clusters with a strong galaxy-driven evolution are expected to be important as observed in the simulations. Nevertheless this coefficient is, as well, dependent on the orbital phase as shown by Grillmair (1992).

From our N-body simulations (CLM99), using multi-mass King-Michie models, we show that the tidal tails are populated mainly by the lighter stars of the pruned globular cluster, because of its mass segregation. In Fig. 31, we present the evolution of the mass function slope (assumed to be a power-law) for a simulation with a globular cluster on polar orbit (CLM99). The duration of this simulation is too short to observe strong changes in the mass spectrum through the cluster itself, nevertheless it can be seen that the radius of constant mass function slope is slightly expanding during the 800 Myr of the simulation. This is especially true in the inner parts of the cluster (see e.g. the isocontour $\alpha = -2$ on Fig. 30).

Let us compare the amount of tidally stripped stars obtained in our simulations and observations. Because of the magnitude limitation of the plates and films, it is likely that we underestimate the observed tidal tails. The mass of the tidal tails in the case of NGC 5139 has been com-
puted for a Salpeter law: if we assume a steep slope $\alpha = -2.8$ for the mass function in the tidal tails, we get a tail mass equal to about 1 % of the total mass of the cluster, equal to $5.1 \times 10^6 M_\odot$. In spite of the great uncertainty on the star counts of the tidal tails, such a large mass is an upper limit for the tidal tail mass from the simulations (CLM99). It confirms both that NGC 5139 has a genuinely large total mass (Meylan et al. 1995) and that the spectrum mass is likely less steep than $\alpha = -2.8$ in the outer part. All these considerations point toward a mass for the tidal tails between 0.6 and 1.0 % of the total mass of NGC 5139. From N-body simulation performed by Moore (1996) we can note that the presence of tidal tails is the indication of low dark matter content in globular clusters.

NGC 7492 and Pal 12 provide an interesting comparison because of their similar characteristics: low masses ($6 \times 2 \times 10^4 M_\odot$, respectively), low concentrations (1.0 and 0.9, respectively), and large distances from the galactic center (23.5 and 14.7 kpc, respectively). They are also both strongly influenced by the Galaxy: G097 compute $v_{tot}/v_{exp} = 77.8$ and 17.9, respectively. Nevertheless, their tidal tails appear strongly different, with a very extended structure for Pal 12 and very tiny one for NGC 7492. The last gravitational shock suffered by NGC 7492 has allowed the surface density of the unbound stars to fade along the cluster orbit. We estimate the last tidal shock suffered by Pal 12 to be about 350 Myr.

**Table 5.** Characteristics of the tails. We indicate a reliability level from 0 (reliable, no observational bias) to 5 (unreliable) for the observed overdensities (tidal tails) around these clusters. The position of the cluster in the galaxy is given through its distance to the sun ($R_\odot$), to the galactic center ($R_{GC}$) and to the plane ($Z$). We give an indication of the alignment of the tidal tails perpendicular to the galactic plane (1), aligned with the galactic center (2) and with no correlation relative to any of these two directions (3). † OP: Orbital path, DS: disk shocking, BS: bulge shocking (+ means both processes are probably at play; / means probably one of the two processes).

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| Cluster Name | Observed size (pc) | Bias | Reliability | $R_\odot$ (kpc) | $R_{GC}$ (kpc) | $Z$ (kpc) | Alignment | Type† |
|--------------|-------------------|------|-------------|----------------|----------------|---------|-----------|-------|
| NGC 104      | 150               | SMC  | 4           | 4.1            | 7.3            | -2.9    | 1/2       | DS/BS |
| NGC 288      | 350               | gal. | 1           | 8.1            | 11.4           | -8.1    | 1/2       | DS/BS |
| NGC 1261     | 100               | gal. | 3           | 15.2           | 17.1           | -12.0   | 2         | BS/OP |
| NGC 1851     | 130               | dust+gal.| 2  | 11.7            | 16.3           | -6.7    | 2         | OP    |
| NGC 1904     | 130               | dust+gal.| 1  | 12.2            | 18.1           | -6.3    | 1/2       | DS/OP |
| NGC 2298     | 200               | dust  | 3           | 10.4           | 15.4           | -2.9    | 2         | OP/BS |
| NGC 4372     | 5                 | dust  | 5           | 4.6            | 6.9            | -0.8    | –         |       |
| NGC 5139     | 170               | dust  | 2           | 4.9            | 6.3            | 1.3     | 1         | DS    |
| NGC 5272     | 150               | gal.  | 4           | 9.7            | 11.6           | 9.5     | 1         | DS    |
| NGC 5694     | 300               | gal.  | 1           | 33.0           | 27.5           | 21.7    | 2         | BS/OP |
| NGC 5824     | 450               | dust+gal.| 4  | 32.2           | 26.1           | 26.1    | 1         | DS/OP |
| NGC 5904     | 80                | gal.  | 2           | 7.0            | 6.0            | 5.1     | 1/2       | DS/BS |
| NGC 6205     | 60                | dust  | 1           | 6.8            | 8.2            | 1.3     | 2         | BS    |
| NGC 6254     | 150               | dust  | 4           | 4.1            | 4.7            | 1.6     | 3         | OP    |
| NGC 6397     | 60                | dust  | 5           | 2.2            | 6.1            | 0.5     | –         |       |
| NGC 6535     | 300               | dust  | 3           | 6.6            | 3.9            | 1.2     | 2         | DS+BS |
| NGC 6809     | 190               | dust  | 4           | 5.1            | 4.0            | -2.1    | 3         | OP    |
| NGC 7492     | 100               | gal.  | 1           | 24.3           | 23.5           | 21.8    | 2         | BS    |
| Pal 5        | 200               | gal.  | 4           | 21.8           | 17.2           | 15.7    | 3         | OP    |
| Pal 12       | 400               | gal.  | 3           | 17.8           | 14.7           | 13.2    | 3         | OP    |
```

6. Conclusions

We have observed 20 galactic globular clusters with multicolor Schmidt plates and films on wide fields. Field and cluster stars are sorted in the color-magnitude plane. A star-count analysis is performed on the color selected stars to study the overdensities that can be attributed to the stars stripped from the globular clusters by tidal shocks (disk/bulge) as well as from internal dynamical evolution. We use the wavelet transform in order to enhance the weak tidal structures at large scales and in order to filter the high background noise at low galactic latitude. After highlighting the observational biases resulting from dust extinction and background galaxy clustering at faint magnitudes, we reach the following conclusions:
– All the clusters observed, which do not suffer from strong observational biases, present tidal tails, tracing their dynamical evolution in the Galaxy (evaporation, tidal shocking, tidal torquing, and bulge shocking).

– The clusters in the following sub-sample (viz. NGC 104, NGC 288, NGC 2298, NGC 5139, NGC 5904, NGC 6535, and NGC 6809) exhibit tidal extensions resulting from a shock, i.e. tails aligned with the tidal field gradient.

– The clusters in another sub-sample (viz. NGC 1261, NGC 1851, NGC 1904, NGC 5694, NGC 5824, NGC 6205, NGC 7492, Pal 5, and Pal 12) present extensions which are likely tracing the orbital path of the cluster with various degrees of mass loss.

– NGC 7492 is a striking case because of its very small extension and its high destruction rate driven by the galaxy as computed by GO97. Its dynamical “twin” for such an evolution, namely Pal 12, exhibits, on the contrary, a large extension tracing its orbital path, with a possible shock which happened more than 350 Myr.

– The velocity diffusion of the stripped stars is tentatively estimated, in one case (viz. NGC 6254), to be similar to the cluster velocity dispersion.

– Thanks to the relatively small distance of NGC 5139 and its high release of unbound stars during its current disk shocking, we estimate the mass loss to be between 0.6 and 1% of the cluster total mass, taking into account a possible mass segregation in the cluster halo. This mass loss rate is consistent with our estimates from N-body simulations (CLM99).

– The second break in the surface density slope, apart from the break at the tidal radius (cf. the case of NGC 6254) could be an indicator of some recent gravitational shocks, with the $Q_1$ indicator displaying a range of values between -0.9 and -2. The latter is likely overestimated because of the uncorrected crowding towards the clusters.

The use of better quality data, e.g. wide-field CCD observations, combined with the present star-count method will allow in a near future to get rid easily of the observational biases and to obtain a better color selection thanks to a more accurate photometry. These observations will provide more precise observational estimates of the mass loss rates for different regimes of galaxy-driven cluster evolution. With the help of numerical simulations and accurate proper motions, it will be possible to constrain efficiently the parameters describing the galactic potential (disk scale-height, surface density, bulge size). In case of a flat dark matter halo (Pfenniger et al. 1994), the tidal shock on the globular clusters would be enhanced, depending on the surface density and the scale-height of this dark matter halo. Pal 2 is a good candidate to probe such dark matter halo flattening, because of its small distance to the galactic plane ($Z = -2.2$ kpc) and its relatively large distance to the galactic center (21.6 kpc), placing this cluster in a region where the tidal shocking by the disk only is expected to be low.

**Fig. 30.** Variations with time of the slope of the mass function fitted by a power-law (-2.35 for a Salpeter law). The simulation is from CLM99.

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