The tidal tails of NGC 5466

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ABSTRACT

The study of substructure in the stellar halo of the Milky Way has made a lot of progress in recent years, especially with the advent of surveys like the Sloan Digital Sky Survey (SDSS). Here, we study the newly discovered tidal tails of the Galactic globular cluster NGC 5466. By means of numerical simulations, we reproduce the shape, direction and surface density of the tidal tails, as well as the structural and kinematical properties of the present-day NGC 5466. Although its tails are very extended in SDSS data ($\gtrsim 45^\circ$), NGC 5466 is only losing mass slowly at the present epoch and so can survive for probably a further Hubble time. The effects of tides at perigalacticon and disc-crossing are the dominant causes of the slow dissolution of NGC 5466, accounting for $\gtrsim 60$ per cent of the mass loss over the course of its evolution. The morphology of the tails provides a constraint on the proper motion – the observationally determined proper motion has to be refined (within the stated error margin) to match the location of the tidal tails.

Keywords: methods: N-body simulations – globular clusters: individual: NGC 5466 – Galaxy: halo – Galaxy: kinematics and dynamics.

1 INTRODUCTION

Within the last few years, it has become more and more obvious that the Milky Way stellar halo is dominated by substructure, particularly dwarf galaxies, clouds, and tidal tails. Data from the Sloan Digital Sky Survey (SDSS; York et al. 2000) have revealed abundant examples of streams and substructure. For example, Belokurov et al. (2006b) used a simple colour cut $g - r < 0.4$ to map out the distribution of stars in SDSS Data Release 5 (DR5). The ‘Field of Streams’, an RGB-composite image composed of magnitude slices of the stellar density of these stars, showed the overlap of the leading and trailing arm of the well-known Sagittarius stream and the Monoceros ring very clearly. Also prominent was a new stream, which did not have an identified progenitor, and was called the ‘Orphan Stream’ by Belokurov et al. (2006b). The observational data on the Orphan Stream (Belokurov et al. 2007) were used by Fellhauer et al. (2007) to argue that its progenitor may be the newly discovered disrupting dwarf galaxy UMa II (Zucker et al. 2006).

Tidal tails have proved to be an important diagnostic of the Galactic potential. Especially the tails of the dissolving Sagittarius dwarf galaxy (see e.g. Ibata, Gilmore & Irwin 1994; Majewski et al. 2003; Helmi 2004; Johnston, Law & Majewski 2005), which wrap around the Milky Way, are an excellent tracer of the strength and shape of the potential. Fellhauer et al. (2006) have shown with their numerical models that the bifurcation of the Sagittarius stream as seen in the ‘Field of Streams’ is composed of two wraps of the tidal tails and can only be reproduced if the orbital precession is small, that is, if the Milky Way dark matter halo is close to spherical.

Extratidal extensions and onsets of tidal tails have been claimed around a number of Galactic globular clusters in recent years (Meylan, Leon & Combes 2001). The most spectacular and convincing discovery remains the long and thin tail from the disrupting globular cluster Pal 5 (Odenkirchen et al. 2001; Rockosi et al. 2002; Odenkirchen et al. 2003). The tails extend at least 4 kpc from the cluster in the leading and trailing direction and contain more mass than the remaining cluster.

Recently, two different groups (Belokurov et al. 2006a; Grillmair & Johnson 2006) claim to have detected tidal tails of various extents around the disrupting globular cluster NGC 5466. This is an old, metal-poor ([Fe/H] = −2.22) cluster, lying at Galactic coordinates $l = 42.15$, $b = 73.59$. In Belokurov et al. (2006a), the observed tails of NGC 5466 are not as long as those of Pal 5, stretching about 2° or 500 pc in either direction. Grillmair & Johnson (2006) reported afterwards that they found evidence for a much larger extension of the tidal tails of NGC 5466. They claimed that the leading arm extends over $\sim 30^\circ$ and the trailing arm extends at least $15^\circ$, before it leaves the area covered by SDSS. This finding makes the tails of NGC 5466 even longer, but much fainter, than the tails of Pal 5.

The aim of our paper is to confront these claims with theoretical expectation, as well as to study the survival of the tails.

The following data for NGC 5466 are taken from various sources in the literature (Pryor et al. 1991; Harris 1996; Lehmann & Scholz...
The Galactic disc is modelled by a Miyamoto–Nagai (L)ogarithmic halo) is a superposition of three components. The halo is represented by a Hernquist (hereafter denoted by DB). It consists of a superposition of three components. The halo is represented by a Hernquist potential: 

\[ \Phi_{\text{halo}}(r) = \frac{1}{2} v_0^2 \ln \left( 1 + \frac{r^2}{d^2} \right), \]  

with \( v_0 = 181 \text{ km s}^{-1} \) and \( d = 12 \text{ kpc} \) (and \( r \) is the spherical radius). The Galactic disc is modelled by a Miyamoto–Nagai potential:

\[ \Phi_{\text{disc}}(R, z) = -\frac{G M_d}{\sqrt{R^2 + (b + \sqrt{z^2 + c^2})^2}}, \]  

with \( M_d = 10^{11} \text{ M}_\odot \), \( b = 6.5 \text{ kpc} \) and \( c = 0.26 \text{ kpc} \) (where \( R \) and \( z \) are cylindrical coordinates). The bulge is represented by a Hernquist potential

\[ \Phi_{\text{bulge}}(r) = -\frac{G M_b}{r + a}, \]  

using \( M_b = 3.4 \times 10^{10} \text{ M}_\odot \) and \( a = 0.7 \text{ kpc} \).

For comparison, we also use the Galactic potential suggested by Dehnen & Binney (1998) (hereafter denoted by DB). It consists of three disc components, namely the interstellar medium (ISM), the thin and the thick discs, each of the form

\[ \rho_{\text{disc}}(R, z) = \frac{\Sigma_d}{2z_d} \exp \left( -\frac{R_m}{R} - \frac{R}{R_d} - \frac{|z|}{z_d} \right). \]  

With \( R_m = 0 \), equation (4) describes a standard double exponential disc with scalelength \( R_d \), scaleheight \( z_d \) and central surface density \( \Sigma_d \). For the stellar discs, \( R_m \) is set to be zero, while for the ISM disc, we allow for a central depression by setting \( R_m = 4 \text{ kpc} \) (Dehnen & Binney 1998). In addition to the the disc potential, we use the analytic potential corresponding to two spheroidal density distributions for the halo and the bulge in the form

\[ \rho(R, z) = \rho_0 \left( \frac{m}{r_0} \right)^{-\gamma} \left( 1 + \frac{m}{r_0} \right)^{-\beta} \exp \left( -\frac{m^2}{r^2} \right), \]  

where

\[ m = \sqrt{R^2 + \frac{z^2}{q^2}}. \]  

We choose the parameters of our DB model according to the best-fitting model 4 in the paper of Dehnen & Binney (1998). In Fig. 1, we compare the two potentials. For both, the circular velocity at the solar radius is 220 km s\(^{-1}\). However, the ML model contains more mass within a given radius than the DB model.

### 2.2 Initial model and orbit for NGC 5466

As an initial model for the star cluster, we choose a Plummer (1911) sphere:

\[ \rho(r) = \frac{3M_{\text{pl}}}{4\pi R_{\text{pl}}^3} \left( 1 + \frac{r^2}{R_{\text{pl}}^2} \right)^{-5/2}, \]  

with \( R_{\text{pl}} \) being the scalelength of the Plummer sphere, which is identical to the half-light radius, and \( M_{\text{pl}} \) being the total mass. This is a fairly good representation of a star cluster, especially a young one. However, due to tidal shaping and internal evolution at later stages, a King (1966) model usually fits the photometric data better. The advantage of a Plummer model is that all physical quantities are analytically accessible.

The initial Plummer model has a half-light radius of 10 pc, an initial mass of \( 7 \times 10^5 \text{ M}_\odot \) and is represented by \( 10^6 \) particles. The numerical set-up of the particles is performed using the algorithm of Aarseth, Henon & Wielon (1974). We checked that our initial model is able to survive for a Hubble time by comparing our initial configuration with the dissolution times given in Baumgardt & Makino (2003) (see their fig. 3). As the orbit of NGC 5466 is most of the time located far out in the halo, it is well represented by the uppermost lines in Baumgardt & Makino (2003), giving us a dissolution time of a few Hubble times.
The tidal tails of NGC 5466

3 JUSTIFICATION OF PARTICLE-MESH SIMULATIONS

To simulate the evolution of the tails of NGC 5466, we use the particle-mesh SUPERBOX package (Fellhauer et al. 2000). A particle-mesh code has the great advantage that we can use millions of particles (which represent equal-mass phase-space elements rather than single stars) and trace the faint tails very accurately. However, such a code is often not suitable for simulations of globular clusters, because it neglects the internal evolution due to two-body relaxation completely.

The reason why SUPERBOX is none the less a valid method for the modelling of NGC 5466 is understood on examining the parameter

\[ \beta = \frac{t_{\text{relax}}}{t_{\text{shock}}} \]  

(Gnedin, Lee & Ostriker 1999):

Here, \( t_{\text{relax}} \) denotes the relaxation time-scale, which amounts to \( \sim 3.9 \) Gyr for our initial model and to \( \sim 3.4 \) Gyr for the present state of the globular cluster. Additionally, \( t_{\text{shock}} \) denotes the disc shock time-scale, which is the time-scale on which the cluster is destroyed by disc shocks. Using the formula from Gnedin et al. (1999), we have

\[ t_{\text{shock}} = \frac{3}{4} P_{\text{disc}} v^2 \omega^2_h \]  

(9)

where \( P_{\text{disc}} \) is the period of the disc-crossings, \( v \) is the velocity with which the object crosses the disc, \( \omega_h \) denotes the ratio of velocity dispersion to half-mass radius \( r_h \) of the object and finally \( r_h \) is the acceleration perpendicular to the disc. Using our simulation data, we derive a disc shock time-scale of about 110 Gyr. This gives a

\[ \beta = 0.03 \pm 0.01, \]  

which holds for both Galaxy models within the errors. The concentration

\[ c = \log \left( \frac{r_{\text{tidal}}}{r_h} \right) \]  

(10)

of our initial model and the star cluster today is of the order of unity. If we now place our initial model in fig. 13 of Gnedin et al. (1999), we see that it falls in the regime where shocks are more important than internal evolution, but also in the regime where the star cluster survives for a Hubble time. Still, the location of our model is close to the border line (at \( c \approx 1 \) it is \( \beta = 0.01 \)) where internal evolution becomes dominant. It is interesting to compare NGC 5466 with the well-studied case of Pal 5, which has \( c = 0.6 \) and \( \beta = 10 \). Pal 5 will most likely be destroyed at its next disc-crossing (Dehnen et al. 2004). By contrast, NGC 5466 has a good chance of surviving even for the next Hubble time!

To demonstrate that the internal evolution has no major effect, we perform two \( N \)-body simulations with \( 10^7 \) particles in the ML potential using NBODY4 (Aarseth 1999) and compare to the SUPERBOX results. In the first simulation, we use an equal mass for all particles and neglected stellar evolution. In the second simulation, we adopt a mass function which is present after the initial phase of violent mass loss caused by the evolution of high-mass stars (first few tens of Myr). In practice, this means another 20 per cent has to be added to the initial mass to account for the mass loss due to supernovae, and stellar winds, as well as the stars which become unbound due to this mass loss. For the remaining stars, stellar evolution in NBODY4 is switched on. Fig. 3 shows, by extrapolating the mass loss in the direct \( N \)-body simulations linearly, that the additional mass loss due to two-body relaxation and stellar evolution amounts at the very most to about one-third of the total mass loss. The linear extrapolation of the mass loss in this mass regime is justified by appeal to the work of Baumgardt & Makino (2003). In other words, disregarding the initial mass loss when the star cluster blows away its gaseous envelope (which depends mainly on the star formation efficiency) and the violent stellar evolution in the first few tens of Myr, the dominant cause of mass loss during the long-term evolution of NGC 5466 is the tidal field of the MW.

Having established that internal disruptive processes (e.g. twobody relaxation) are of minor importance, we now investigate the major external destruction processes. As is visible in Fig. 3, the mass loss happens in short bursts, which we show in detail in Fig. 4. The first (black) vertical line marks the time of perigalacticon, while the second (red) line marks the time when the cluster crosses the disc (\( z = 0 \)). The mass loss due to the tidal field is steep before
and at perigalacticon, and becomes more gradual after perigalacti-
con. There is an additional steepening of the mass loss when the
cluster passes the centre of the disc. However, as the small inset
in Fig. 4 shows, this mass loss is only about one-sixth of the total
mass loss at the combined perigalacticon and disc-passage. Thus,
it is the tidal field of the disc (the perigalacticon is well outside
the bulge region) which causes most of the mass loss, and the ac-
tual disc shock when the cluster passes through the centre of the
disc is of secondary importance. This finding is consistent with the
rather large time-scale for disc shocks (110 Gyr) of the previous
section.

The dissolution of tidally limited star clusters has been studied
in detail many times before. Henon (1961) found that a cluster be-
comes completely dissolved in about $\sim 2 t_{\text{relax}}$, and this result has
been confirmed by many subsequent investigators (see e.g., Lee &
Ostriker 1987). Since the current relaxation time is $\sim 3.4$ Gyr, we
may already anticipate that total amount of mass loss during the
last Hubble time is $\sim 20$ per cent of the initial mass (assuming no
stellar evolution). Furthermore, if there exists a mass function, the
life expectancy due to steady tidal field alone could become as short
as $\sim 7 t_{\text{relax}}$ (Lee & Goodman 1995). Since the disc shock time-scale
is much longer, the mass loss due to disc shocking alone should be
quite small.

4 TIDAL TAIL RESULTS

4.1 The tail morphology and the proper motion

One of the advantages of SUPERBOX is that it has high-resolution
subgrids, which stay focused on the simulated objects and travel
with them through the simulation area. This is important in studying
the morphology of the tenuous and diffuse tidal tails. Within the
innermost grid, we resolve the globular cluster at a resolution of
1.7 pc. The grid with medium resolution is chosen to resolve the
tidal tails close to NGC 5466 with a resolution of 16.7 pc.

In Fig. 5 (first two panels), we plot the bound mass of our models
in two Galactic potentials (DB and ML). In both cases, the mass
loss is strong in the first 2–3 Gyr and then tends to level off during
the later stages of the evolution. The mass loss is mainly related to
each disc-crossing near perigalacticon and the mass stays almost
constant during the rest of the orbit. This is the major reason why
in the DB potential the mass loss over 10 Gyr of evolution is less
than that in the ML potential – the star cluster has had fewer disc-
crossings. In the ML potential, the cluster loses about 18 per cent
of its initial mass, whilst the cluster in the DB potential only suffers a
mass loss of 14 per cent (with a fluctuation of only a few particles out
of 1 000 000). However, these mass losses are only lower limits, as
there will be a smaller, but not negligible, contribution from internal
relaxation effects.

In the top left-hand panel of Fig. 6, we show the data on the tails
of NGC 5466 reproduced from Belokurov et al. (2006a), who used
neural networks to reconstruct the probability density distribution.
The contours correspond to level curves of equal neural network
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Figure 5. Mass loss of NGC 5466 in the DB potential (left-hand panel), in the ML potential (middle panel), and in the ML potential with the revised proper motions (right-hand panel).

Figure 6. Contour plots of the tails (the model contours have logarithmic spacing). The solid green line shows the actual orbit, and the red circle shows the size of the actual tidal radius. Top left-hand panel: observations using SDSS by Belokurov et al. (2006a). Top right-hand panel: simulation using the DB potential. Lower left-hand panel: ML potential. Lower right-hand panel: ML potential combined with the revised proper motion. The tidal tails in the ML potential are more prominent than those in the DB potential due to the higher mass loss. In all models, tails and orbit (solid green line) are almost aligned. In both the top right-hand and bottom left-hand cases, the very inner tails are closer to the Galactic Centre in the leading arm and away from the Galactic Centre in the trailing arm. This is the other way round in the observations. In the lower right-hand panel, the revised choice of proper motions in equation (11) is used. Now the tails are a better match to the observations (compare the tails close to the cluster with the dashed line, which shows the ‘old’ orbital path).

in declination than the values given in the literature (e.g. Dinescu et al. 1999) to match the observed misalignment. We confirm this result by running another simulation with slightly changed proper motions, namely

\[
\mu_\alpha \cos \delta = -4.7 \text{ mas yr}^{-1}
\]

\[
\mu_\delta = 0.42 \text{ mas yr}^{-1}.
\]  

(11)

This orbit gives a perigalacticon of 5.9 kpc and an apogalacticon of 57.5 kpc. Although the change in proper motion does not make a significant difference to the mass-loss rate, as shown in the right-hand panel of Fig. 5, it does improve the match with the location of the observed tidal streams much better, including the misalignment. In the lower right-hand panels of Fig. 6, we see that the inner parts of the leading tails are now slightly below the old proper motion vector, whilst the inner parts of the trailing tails are now slightly above.

4.2 The tail densities and extent

Fig. 7 shows all-sky views of the tidal tails, together with density profiles obtained by counting particles. The surface density of the tidal tails falls off along the innermost tails very steeply and stays at a very low density of \(20–50 \text{ M}_\odot \text{ deg}^{-2}\) throughout the tails. These low densities are very hard to detect, even in surveys like SDSS. Grillmair & Johnson (2006) found long, almost linear and very tenuous tidal extensions to NGC 5466 using a matched filter. Although these extensions are hard to see in the SDSS data, they do receive some support from the simulations presented here. The tails of our model with the revised proper motion extend over \(\sim 100^\circ\) on the sky. Grillmair & Johnson (2006) claim that the average density of the tails is about \(10–20 \text{ stars deg}^{-2}\), which is also in good agreement with our estimate. Interestingly, at the point where Grillmair & Johnson (2006) start to lose track of the leading arm,
our model is close to its apogalacticon and the tails are spread out much wider than is the case close to the cluster.

Although our simulation with the revised proper motion provides a good representation of the data, it is clearly not unique. In particular, it is interesting to understand the variety of tidal tail morphology for NGC 5466, especially as forthcoming deeper photometry will provide stronger constraints on the modelling. Accordingly, we perform a suite of SUPERBOX simulations to investigate how the choice of proper motion influences the mass loss and hence the properties of the tidal tails. As a constraint, we only used proper motions which are within the $1\sigma$ error range of the observed value (Dinescu et al. 1999) and also require that the orbital path near the cluster aligns with the tails found by Belokurov et al. (2006a), that is, have the same projected orbital path as our refined set of proper motion. All-sky views of selected simulations are shown in Fig. 8 and show significant differences in the morphology and the properties of the tails. Table 1 gives the parameters and the results for the entire suite of simulations.

The number of degrees in right ascension over which the tail is detectable represents a measure for the length of the tails. The mean density of the tails is calculated in the following way. We examine one degree in right ascension $\alpha$ and search for the highest surface density in the tails for each degree in declination $\delta$. From these values, we compute the average surface density over the range of right ascension for which the tails are present. The maximum density given in the table is computed from the square degree of the tails with the highest surface density. Effects of varying distances are not taken into account. Table 1 shows clearly that the closer the orbit is to the Galactic Centre, the more severe is the mass loss and the higher is the density in the tails.

### 4.3 The remnant NGC 5466

Let us consider the internal properties of our remnant cluster in a representative simulation. We choose the one which uses the ML potential and the revised proper motions, shown in the lower right-hand panels of Fig. 6. For this simulation, Fig. 9 shows the surface density and velocity dispersion profiles of the final cluster. Adopting the data from Harris (1996) (updated values from 2003), the cluster has a central surface brightness of 21.28 mag arcsec$^{-2}$. This is in good agreement with our simulation, for which the central surface brightness is 20.6 mag arcsec$^{-2}$, especially taking into account that our particle-mesh code neglects internal evolution, which would lead to higher densities in the core. Also, the half-light radius in our simulation is 10 pc and corresponds well with the observed values of 10.4 pc (Harris 1996) and 13.1 pc (Pryor et al. 1991). The actual tidal radius in our model is 75 pc (using the Jacobi limit as given in Binney & Tremaine 1987) and is less than the 158 pc stated in Harris (1996) (158 pc) or 97 pc in Lehmann & Scholz (1997), but only slightly larger than the radius of 61 pc found by Pryor et al. (1991). Note that, observationally speaking, $r_{\text{tidal}}$ is determined by fitting a King (1966) profile to the surface brightness distribution, which does not correspond exactly to the theoretical definition. According to our simulations, the tidal radius at the last perigalacticon was about 38 pc.

While the surface density in the inner parts is not much affected by the mass loss, the central velocity dispersion is reduced by approximately 10 per cent. Also visible is a rise in the line-of-sight velocity dispersion in the outer parts, which starts already within the actual tidal radius. This is due to the fact that all line-of-sight measurements are contaminated by unbound stars streaming in front or behind the star cluster. While they do not affect the central values because of their low number, their effect is easily measurable in the outer parts where the densities of the bound stars are much lower.

### 5 CONCLUSIONS

We have presented numerical simulations of the formation and evolution of the tidal tails of the globular cluster NGC 5466. We used direct $N$-body codes to argue that the evolution of the cluster is dominated by external effects rather than internal relaxation, and then grid-based codes to trace the faint tidal tails. This novel, hybrid approach is well suited to map out the detailed morphology of the low-density tails of NGC 5466.

Naively, we might expect that a low-mass cluster with observed and very lengthy tails on a disc-crossing orbit would not be able to survive for too much longer. However, simulations by Dehnen et al. (2004) have already shown that the disrupting globular cluster Pal 5 has survived for at least many gigayears in a tidally dominated and out-of-equilibrium state, although Pal 5 probably will be destroyed at the next disc-crossing. Here, we have demonstrated that a progenitor cluster of NGC 5466 could survive substantially longer, for at least a few Hubble times, with its extensive but tenuous tidal tails gradually wrapping around the whole Galaxy.

The evolution of NGC 5466 is mainly driven by tidal stripping at each perigalacticon and disc-crossing combination. Although not entirely negligible, internal effects (two-body relaxation and evaporation of stars driven by post-core collapsed processes, Lee & Goodman 1995) play a much less important role in the mass loss. It is this property which allows us to study the tidal tails using grid-based codes rather than the more cumbersome direct $N$-body codes. If the observationally determined mass-to-light ratio of $\sim 1$ is correct, then the initial mass of NGC 5466 is $\sim 7 \times 10^4 M_\odot$. By initial
The tidal tails of NGC 5466

Figure 8. Simulations with different proper motions. The rows show from the top to bottom panel: the projection of the tidal tails in $\alpha$ and $\delta$, the distance distribution of the tails versus $\alpha$ and finally the surface density of the tails versus $\alpha$. The columns show first the simulation with the smallest magnitude in proper motion, our best-fitting model and finally the model with the highest magnitude of proper motion.

Table 1. Results of the suite of simulations investigating the relation between orbit and density of the tidal tails. The columns give the following numbers: the absolute value of the proper motion, the proper motion in $\alpha$ and $\delta$, the peri- and apo-galacticon distances, the mean density of the tails, the maximum density in the tails, the extent of the tails, and the final mass of the cluster in units of the initial mass.

| $|\mu|$ (mas yr$^{-1}$) | $\mu_\alpha \cos \delta$ (mas yr$^{-1}$) | $\mu_\delta$ (mas yr$^{-1}$) | $R_{\text{peri}}$ (kpc) | $R_{\text{apo}}$ (kpc) | $\Sigma_{\text{mean}}$ (M$_\odot$ deg$^{-2}$) | $\Sigma_{\text{max}}$ (M$_\odot$ deg$^{-2}$) | Extent (\degree) | Final cluster mass ($M_\odot$) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 4.40            | -4.40           | 0.00            | 4.9             | 42.9            | 30.6            | 81.5            | 249             | 0.74            |
| 4.61            | -4.60           | 0.30            | 5.7             | 50.8            | 26.7            | 60.5            | 244             | 0.79            |
| 4.72            | -4.70           | 0.42            | 5.9             | 57.5            | 25.5            | 56.3            | 244             | 0.80            |
| 4.84            | -4.80           | 0.60            | 6.4             | 61.5            | 23.4            | 72.6            | 239             | 0.83            |
| 5.06            | -5.00           | 0.80            | 7.0             | 73.0            | 21.5            | 54.0            | 239             | 0.87            |
| 5.30            | -5.20           | 1.00            | 7.4             | 88.1            | 19.1            | 47.0            | 230             | 0.89            |
| 5.60            | -5.45           | 1.30            | 8.0             | 116.9           | 14.9            | 31.6            | 224             | 0.92            |

mass, we do not mean the embedded mass of the star cluster at its formation inside a gas cloud. If the star formation efficiency is low, a star cluster can lose about $\sim$70 per cent of its initial mass in stars when the gas gets blown out by high-velocity winds or supernova explosions. The rapid stellar evolution of high-mass stars then adds another extreme mass loss of $\sim$20 per cent in the first few tens of Myr. After this initial phase of rapid evolution, the cluster reaches a quasi-equilibrium. This is the starting point of our simulations and therefore our initial mass refers to this point in time.

Our numerical simulations reproduce the observational results of both groups who have recently studied the tidal tails NGC 5466 with SDSS data. Mapping out the tails close to the globular cluster, Belokurov et al. (2006a) found that the leading tail emerges from the side pointing towards the Galactic Centre and returns to the orbital path from outside, while the trailing tail emerges from the side opposite to the Galactic Centre and returns to the orbital path from within. With our simulations, we showed that the proper motion of the globular cluster has to be smaller in declination and/or larger in right ascension than reported by Dinescu et al. (1999) to account for the position of the tidal tails. We propose a new set of proper motions, $\mu_\alpha \cos \delta = -4.7$ mas yr$^{-1}$, $\mu_\delta = 0.42$ mas yr$^{-1}$ for which the tail morphology is correctly reproduced. This differs from the observationally determined one by $-0.05$ and $-0.38$ mas yr$^{-1}$, respectively. These changes are within the error margins of the observed proper motion ($\pm 0.82$ mas yr$^{-1}$).

The surface density of the tidal tails falls off along the innermost tails very steeply and stays at a very low density of $20-50M_\odot$ deg$^{-2}$ throughout the tails. These low densities are very hard to detect, even in surveys like SDSS. Grillmair & Johnson (2006) found long, almost linear and very tenuous tidal extensions to NGC 5466 using a matched filter approach. Their work is supported by the simulations in this paper, which show that the very long
Figure 9. Left-hand panel: surface density distribution of our model of the NGC 5466 remnant. The left-hand ordinate shows $M_{\odot} \text{pc}^{-2}$, and the right-hand ordinate shows mag arcsec$^{-2}$ using the mass-to-light ratio of 1 from the literature. The inner part is still well fitted by the initial Plummer profile, while the outer parts are better fitted by a steeper power law with index $-4.5$. The deviation is visible in the region from tidal radius at perigalacticon to tidal radius at apogalacticon. The vertical lines denote the tidal radius now (solid line) and at the last perigalacticon (dashed line), while the dotted lines mark the grid boundaries with changes in resolution. Right-hand panel: velocity dispersion profile. The green open squares denote the 3D velocity dispersion measured in concentric shells around the cluster centre, and the crosses are the line-of-sight velocity dispersion measured in concentric rings around the cluster centre. The curves show the profile of the initial model. The vertical lines are as in the left-hand panel.

($\gtrsim 100^\circ$), faint tidal tails are expected. The tails in our simulation have roughly the same surface density as found by Grillmair & Johnson (2006).

In the future, deeper photometry, radial velocities and – thanks to the GAIA and SIM satellites – proper motions of individual stars in the tidal tails may become available. Mapping out the structure of the tails of globular clusters and dwarf galaxies will then provide powerful constraints on the Galactic potential. This work, together with the observational papers of Belokurov et al. (2006a) and Grillmair & Johnson (2006), has shown that NGC 5466 is a prime target for such studies of cold streams. Its tidal tails, though faint, are the longest so far claimed for any Milky Way globular cluster.

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