A Possible Formation Scenario for the Ultra-Massive Cluster W3 in NGC 7252

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ABSTRACT

The intermediate age star cluster W3 (age \( \approx 300–500 \) Myr) in NGC 7252 is the most luminous star cluster known to date with a dynamical mass estimate of \( 8 \pm 2 \cdot 10^7 \) M\(_\odot\). With an effective radius of about 17.5 pc and a velocity dispersion of 45 kms\(^{-1}\), this object may be viewed as one of the recently discovered ultra-compact dwarf galaxies (UCDs). Its intermediate age, however, precludes an origin as a stripped nucleated dwarf elliptical galaxy.

The galaxy NGC 7252 is a merger remnant from two gas-rich disc galaxies. Interactions between two gas-rich galaxies lead to bursts of intense star formation. The age of the interaction and the age of W3 are in good agreement, suggesting that W3 probably formed in the starburst.

We propose a formation scenario for W3. Observations of interacting galaxies reveal regions of strong star formation forming dozens up to hundreds of star cluster in confined regions of up to several hundred parsec in diameter. The total mass of new stars in these regions can reach \( 10^7 \) or even \( 10^8 \) M\(_\odot\). By means of numerical simulations we have shown that the star clusters in these regions merge on short time-scales of a few Myr up to a few hundred Myr. We apply this scenario to W3 and predict properties which could be observable and the future evolution of this object.

This work lends credence to the notion that at least some of the UCDs may be evolved star cluster complexes formed during early hierarchical mergers.

Key words: galaxies: NGC 7252 – galaxies: interactions – galaxies: formation – galaxies: star clusters – galaxies: dwarfs – methods: N-body simulations

1 INTRODUCTION

In the merger remnant system NGC 7252 Maraston et al. (2004) found the most luminous star cluster known to date, W3. They determined its mass via two independent ways. First they used the total luminosity of \( M_V = -16.2 \) and a stellar \( M/L \) derived from a single stellar population model to estimate its mass to be \( 7.2 \cdot 10^7 \) M\(_\odot\). As an independent approach they calculated the dynamical mass by measuring the velocity dispersion, which turned out to be quite high, \( \sigma = 45 \pm 5 \) kms\(^{-1}\), and the effective radius of W3 \( R_{\text{eff}} = 17.5 \pm 1.8 \) pc. This translates to a mass of W3 of \( M_{\text{dyn}} = 8 \pm 2 \cdot 10^7 \) M\(_\odot\) assuming dynamical equilibrium of a spherical object with isotropic velocity distribution. The age of this object is about 300–500 Myr (Maraston et al. 2004 and references therein), which indicates that it probably formed during the merger event of the host system. The projected distance of W3 to the centre of NGC 7252 is about 10 kpc and W3 appears to lie within the optical radius of the galaxy. The size and mass of this object leads to the suggestion that it may be one of the recently discovered ultra compact dwarf galaxies (UCD) found in the Fornax cluster (Hilker et al. 1999; Phillipps et al. 2000), rather than an ‘ordinary’ globular cluster. The UCD galaxies have been suggested to be the cores of stripped nucleated dwarf galaxies (Bekki et al. 2003, Mieske et al. 2004).

We propose instead a formation scenario which is closely related to the massive star-bursts caused by the interaction of two gas-rich disc galaxies. In interacting systems like the Antennae (NGC 4038/39; Whitmore et al. 1999, Zhang & Fall 1999) regions of very intense star-formation arise as a result of the tightly compressed interstellar media. Dozens and up to hundreds of young massive star clusters are observed to form in star cluster complexes (or super-clusters) spanning up to a few hundred pc in diameter. Kroupa (1998) argues that these super-clusters have to be bound objects because their age (\( \approx 10 \) Myr) indicates that they should be already dispersed. Simulating super-clusters, by means of stellar dynamical \( N \)-body simulations, Fellhauer et al. (2002) found that the star clusters within these super-clusters merge on very short time-scales (a few dozens to a few hundred Myr), namely a few crossing-times of the super-cluster.

The resulting merger-objects can be characterised by their large effective radii. They show similar properties like the UCDs (Fellhauer & Kroupa 2002a) or the faint fuzzy star clusters (Fellhauer & Kroupa 2002b) found in a survey of S0 galaxies (Larsen...
& Brodie 2000), that are understood to be morphological types resulting from the merger of at least two late-type galaxies.

To distinguish between the two formation scenarios for UCD galaxies one would need detailed information about the metallicities and ages of the stellar populations inside these objects. Dwarf galaxies have a rather complex mixture of stellar populations, while star clusters form in a single mono-metallic starburst. Unfortunately this information is not yet accessible for objects as distant as the UCDs in Fornax or W3 in NGC 7252.

However, as pointed out by Kroupa (1998), objects as massive as the super clusters firstly can retain stellar winds thereby progressively building up an interstellar medium from which new stars may later form, secondly can capture old field stars during their formation and thirdly accrete gas later-on leading to younger stellar generations. The stellar age and metallicity distribution may thus be very complex in evolved super-clusters.

The age-estimate of W3 points to the possibility that it may have formed during the merger event of the host-galaxy (i.e. out of merging star clusters) rather than it being the stripped core of a dwarf galaxy, which should be very old.

Another indication of the nature of this object would come from a detailed surface-brightness profile. Young massive star clusters formed in the Large Magellanic Cloud in strong star burst regions show ripples in their profiles (Schweizer 2004). This also suggests a formation history through the merging of several objects.

In this project we perform stellar dynamical N-body simulations to show that the merging of star clusters in dense star cluster complexes is able to form massive objects like W3 in NGC 7252. In the next section we describe the setup of our models followed by the results of our investigation. Finally we end with a discussion of our results.

2 SETUP

The simulations are carried out with the particle-mesh code SUPERBOX with high-resolution sub-grids which stay focussed on the simulated objects (Fellhauer et al. 2000).

In our models the super-cluster is initially represented by a Plummer sphere with a Plummer radius of 100 pc and a cut-off radius of 500 pc. The clusters inside this super-cluster have a total mass of $9.9 \cdot 10^7 M_{\odot}$, which leads to a crossing time of the super-cluster of $t_{\text{cr,sc}}=9.3$ Myr. Inside the Plummer sphere of the super-cluster, the 'particles' have positions and velocities according to the Plummer distribution function. The 'particles' themselves are Plummer spheres representing the star clusters with, respectively, Plummer radii of 4 or 10 pc, masses of $10^6$ and $5 \cdot 10^6 M_{\odot}$ and crossing times of 0.75 and 1.32 Myr, being represented by $10^3$ and $5 \cdot 10^5$ particles. Altogether the super-cluster is filled with 75 star clusters, from which 69 are light ones and 6 are of the heavy type to mimic a power law mass spectrum similar (power law index $\alpha = -1.9$) to the one found in the young massive star clusters in the Antennae (Zhang & Fall 1999). To model hundreds of lighter complexes is able to form massive objects like W3 in NGC 7252.

In contrast to our previous models (Fellhauer & Kroupa 2002a,b) where the merger objects were smaller and not that heavy, the merging process here takes more time. After the first clusters have merged and build up a massive and extended object with the remaining clusters within, it is not encounters between clusters and the merger object which govern the merging process (the clusters are already within the object) but dynamical friction acting on the remaining clusters. Nevertheless a massive merger object is present from an early stage on.

The grid-levels of SUPERBOX are chosen in a way that the innermost grids with the highest resolution cover the single star clusters resolving intra-cluster forces and the forces during the merging of two star clusters. The median resolution grid is chosen to cover the area of the whole super-cluster, resolving the forces between the clusters. Finally the outermost, non-moving grid covers the orbit of the super-cluster around the host galaxy. A detailed listing of the grid-parameters can be found in Tab.1.

| Object             | inner grid size | inner grid resol. | medium grid size | medium grid resol. | outer grid size | outer grid resol. |
|--------------------|-----------------|-------------------|------------------|-------------------|----------------|------------------|
| light cluster      | 50.0            | 0.83              | 1000.0           | 16.67             | 50.0           | 0.83             |
| heavy cluster      | 120.0           | 2.00              | 1000.0           | 16.67             | 50.0           | 0.83             |
| merger object      | 120.0           | 2.00              | 1000.0           | 16.67             | 50.0           | 0.83             |

3 RESULTS

In contrast to our previous models (Fellhauer & Kroupa 2002a,b) where the merger objects were smaller and not that heavy, the merging process here takes more time. After the first clusters have merged and build up a massive and extended object with the remaining clusters within, it is not encounters between clusters and the merger object which govern the merging process (the clusters are already within the object) but dynamical friction acting on the remaining clusters. Nevertheless a massive merger object is present from an early stage on.

The top row of Figure 1 shows the contour plot of the merger object (left at $t = 300$ Myr and right at $t = 500$ Myr comprising the suggested age-range of W3). The contours are spaced in magnitude intervals and masses are converted to luminosities taking a mass-to-light ratio of 0.15. According to a single stellar population model run with Starburst99 (Leitherer et al. 1999) a stellar population of
this age has a $M/L = 0.1\text{--}0.2$. In our model these two time-slices mark the transition between the time, when still many star clusters are visible as separate entities and the time when most of the star clusters have already merged or are dissolved within the merger object. The unmerged star clusters also cause little wiggles in the surface density profile. Unfortunately NGC 7252 and thus W3 are too far away to resolve the surface density profile in detail. Wiggles like this are found in resolved young massive star clusters in the LMC (Schweizer 2004).

Another interesting feature of our model is that the merger object shows a cuspy structure with a dynamically cold core. The profile can be fitted by either two King profiles or two exponentials (Fig. 1 middle row) and the velocity dispersion is rising in the innermost part and reaches its maximum beyond the transition between the core and the envelope (Fig. 1 bottom row). The outer part of the velocity dispersion, reaching from the maximum value to the tidal radius, can be fitted with an exponential profile with an exponential scale length of the order of the tidal radius of the object. A detailed listing of the fitting parameters can be found in Table 2.

Beyond the tidal radius the velocity dispersion is rising again due to the large velocities of the extra tidal stars.

In Fig. 2 we show the evolution of the total mass, of the effective radius and of the velocity dispersion of our model, whose dynamical evolution was followed for 5 Gyr. To derive the mass we only take the bound particles into account. The effective radius is taken at the point where the surface brightness has dropped to half of the central value. Finally the 3D-velocity dispersion was derived in concentric shells around the centre of the object. Shown in the figure are the central values of the dynamically cold core as well as the maximum values. The boxes show the values measured for W3. The total mass as well as the maximum velocity dispersion of our model is in reasonable agreement with the data of W3. Only the effective radius of our model is too small compared with W3. It starts off at a value of about 10 pc and it increases slightly until the majority of the star clusters have merged, deforming the core progressively. After the merging process has ceased the core of the merger object stabilises and the effective radius drops to about 5 pc. But note the extremely large value at $t = 700$ Myr. At exactly that time a late merger event of one of the remaining star clusters happened. If our formation scenario is correct then this points to the possibility that we might be observing W3 at the time when a star cluster merges with the core of the object mimicking a large effective radius.

The further dynamical evolution is mainly governed by the tidal shaping of the object due to its eccentric orbit. It leads to a successive mass loss and an increase in the effective radius as well as a decrease in the maximum velocity dispersion, while the central value increases slightly.

Looking at the merger object after 5 Gyr of its dynamical evolution (Fig. 3) shows that this object is very stable against tidal disruption. Also the dynamically cold core is not a transient feature but survives the evolution. The total mass of the object is still of the order of $6 \cdot 10^7 M_\odot$, which is an order of magnitude more than the most massive globular cluster ($\omega$ Cen) of the Milky Way. The relaxation time-scale of this object, adopting the formula from...
Figure 2. Time evolution of characteristic parameters of our model. Total mass (top left panel), thick horizontal line shows the value derived from the luminosity of W3 dashed line and box shows the dynamical mass and the 1σ-uncertainty of W3; Effective radius (top right panel), horizontal line shows the fitted value of W3 and the box around denotes the 1σ-uncertainty; Velocity dispersion (bottom panel): Crosses are the maximum velocity dispersion values and three-pointed stars are the central values. Horizontal line and box again shows the measured value for W3 with 1σ-uncertainty.

Figure 3. Merger Object at 5 Gyr. In the contour plot (outermost contour corresponds to $\Sigma_0 = 25$ mag.arcsec$^{-2}$) and the magnitude scale of the surface density profile $M/L_B = 3.0$ is adopted. The symbols and lines have the same meaning as in Fig. 1.

Figure 4. Central surface brightness, $\mu_{0,B}$, vs absolute photometric B-band magnitude, $M_B$ (the Kormendy diagram). The small dots are data for Milky-Way globular clusters (Harris 1996), Local-Group dwarf galaxies (Mateo 1998) are marked as crosses and elliptical galaxies (Peletier et al. 1990) are shown as open boxes. The newly discovered UCDs are shown by arrows with lower-limits on $\mu_B$ (Phillipps et al. 2001). The line shows the evolution of our merger object from the time of formation until 5 Gyr using a time-dependent $M/L_B$ from a single stellar population model of Starburst99 (Leitherer et al. 1999). Crosses on the line mark the time between 300 and 500 Myr.

Spitzer & Hart (1971), is

$$t_{\text{relax}} = 0.138 \cdot \frac{\sqrt{M_{cl} r_h^{3/2}}}{\langle m \rangle^2 G \ln(0.4 n)},$$

(1)

where $M_{cl}$ is the mass of the object, $r_h$ is the half-radius (151.7 pc at $t = 5$ Gyr), the average stellar mass $\langle m \rangle = 0.4 M_\odot$ (using the universal IMF, Kroupa 2001) and $n$ the number of stars. This leads to $t_{\text{relax}} \approx 4000$ Gyr. This shows that this object might be thought of as a dwarf galaxy rather than a globular cluster, since $t_{\text{relax}}$ is much longer than a Hubble time.

Finally we convert the evolution of the total mass and the central surface density into total luminosity and central surface brightness adopting the mass-to-light ratios from the evolution of a single stellar population calculated with Starburst99 (Leitherer et al. 1999). This enables us to place the evolution of our model into a Kormendy diagram (Fig. 4). It starts above the values for the Knots (super-clusters) in the Antennae, because our super-cluster model is much more massive than the super-clusters seen in the Antennae and evolves down and right to the area above the UCDs and close to $\omega$ Cen.

4 DISCUSSION

With our numerical model we introduce a formation scenario for the ultra-massive ‘star cluster’ W3 found in NGC 7252. We propose that this object may not have formed as one star cluster, but rather as a star cluster complex. The star clusters in this complex have merged and formed W3. These star cluster complexes (super-clusters) are a common feature in interacting late-type galaxies.
We predict how W3 should look like if it would be possible to resolve it. Its age places it at about the transition time between having many remaining star clusters visible inside and the time when all star clusters have already merged. One should see the last surviving star clusters in the stage of merging. This should be also visible as ripples in the surface brightness profile.

Furthermore a merger object as massive as W3 should show a distinct core–envelope structure. The merger object in our calculation had a dense, dynamically cold core and an extended envelope. This core–envelope structure is not a transient feature but a stable configuration. We followed the evolution of our merger object for 5 Gyr and this structure remained. The core is formed out of the merged star clusters. The envelope consists out of the stripped stars, lost by the star clusters during the initial violent merger process. In our previous models the merger objects are not massive enough to keep stripped stars bound and they are lost. In the case of the W3 model the core object is massive enough to retain the stripped stars bound, forming the envelope structure of our model.

W3 is said to be one of the newly discovered ultra-compact dwarf (UCD) galaxies and also one of the most massive ones (Maraston et al. 2004). Other UCDs are found and studied around the central galaxy in the Fornax cluster (NGC 1399) by Hilker et al. (1999), Phillipps et al. (2001) and Mieske et al. (2004). These objects are quite old. There are two competing formation scenarios for UCDs. While Bekki et al. (2003) propose that these objects are the remaining cores of stripped nucleated dwarf galaxies, Fellhauer & Kroupa (2002a) proposed the merging scenario from star cluster complexes as a possible formation process, resulting naturally from the merging of gas-rich galaxies in groups as the groups merge with a galaxy cluster. A possible way to distinguish between the two scenarios would be an analysis of the stellar populations in these objects. While the merging star cluster scenario implies that the stars of the UCDs have more or less the same metallicity and age (this holds at least for the most prominent population formed in the starburst), cores of dwarf galaxies should show a more complex metallicity and age distribution. And as dwarf galaxies are believed to be the oldest building blocks in the universe, the cores should show a prominent very old population. Differentiating between the two scenarios, however, will not be easy because massive merger objects are likely to retain stellar winds, thereby progressively building up an interstellar medium from which new stars may form. They may also accrete interstellar gas and old field stars from their progenitor galaxy (Kroupa 1999).

In the case of W3 the stripping scenario can be completely ruled out. Age estimates of this object range from 300 to 500 Myr, which is also the age of the interaction (NGC 7252 is a merger remnant of two gas-rich disc galaxies). This time is much too short for a nucleus to be stripped of its surrounding dwarf galaxy. If this implies that all UCDs must have formed in the same way or if both scenarios are possible and are realized by nature can not yet be asserted.

Our model is an alternative to the formation of one single massive object, which is believed to be highly unlikely even in extreme starbursts as seen in interacting gas-rich galaxies.

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