Formation of massive globular clusters with dark matter and its implication on dark matter annihilation

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ABSTRACT
Recent observational studies of $\gamma$-ray emission from massive globular clusters (GCs) have revealed possible evidence of dark matter (DM) annihilation within GCs. It is, however, still controversial whether the emission comes from DM or from milli-second pulsars. We here present the new results of numerical simulations, which demonstrate that GCs with DM can originate from nucleated dwarfs orbiting the ancient Milky Way (MW). The simulated stripped nuclei (i.e., GCs) have the central DM densities ranging from 0.1 to several M$_\odot$pc$^{-3}$, depending on the orbits and the masses of the host dwarf galaxies. However, GCs born outside the central regions of their hosts can have no/little DM after their hosts are destroyed and the GCs become the Galactic halo GCs. These results suggest that only GCs originating from stellar nuclei of dwarfs can possibly have DM. We further calculate the expected $\gamma$-ray emission from these simulated GCs and compare them to observations of $\omega$ Cen. Given the large range of DM densities in the simulated GCs, we suggest that the recent possible detection of DM annihilation from GCs should be more carefully interpreted.

Key words: globular clusters: general – globular clusters: individual: Omega Centauri – dark matter

1 INTRODUCTION
The Galactic globular cluster (GC) $\omega$ Cen has a number of very unique characteristics, such as the very large mass (e.g. Meylan et al. 1995), retrograde orbits (e.g. Dinescu et al. 1999), and multiple distinct subpopulations (e.g. Bellini et al. 2018). These unique properties have been investigated both observationally and theoretically (e.g. Meylan & Mayor 1986; Watkins et al. 2013; Baumgardt et al. 2019). Recent observations detected $\gamma$-ray emission from massive GCs like $\omega$ Cen and 47 Tucanae (Abdo et al. 2010; Dai et al. 2020). The source of this $\gamma$-ray emission is still subject to debates. The most popular hypotheses include the presence of millisecond pulsars (Abdo et al. 2010; Dai et al. 2020) and dark matter (DM) annihilation (Gaskins 2016; Brown et al. 2019). For a direct comparison of the two possibilities see Reynoso-Cordova et al. (2019). If the source of the $\gamma$-rays is DM, then the question would be: Where did the DM come from?

It has been suggested that nucleated dwarf galaxies can be transformed into massive GCs like $\omega$ Cen and ultra-compact dwarfs (UCDs) due to tidal stripping of the dwarfs by the strong gravitation field of their host environments ("galaxy threshing"; Bekki et al. 2001; Bekki & Freeman 2003 from here on BF03). In particular $\omega$ Cen has been proposed to be the tidally stripped nucleus of a dwarf galaxy (BF03). This is further supported by its density profile (Ideta & Makino 2004). However, previous simulations did not include a DM halo (Ideta & Makino 2004), which is known to exist in dwarf galaxies (Kormendy & Freeman 2004; Kormendy & Freeman 2016; Das et al. 2019). Therefore, if $\omega$ Cen is the nucleus of a tidally stripped dwarf, could there be any DM left over from the progenitor galaxy? Similar suggestions have been made to explain the elevated mass to luminosity ratio in UCDs (Chilingarian et al. 2011). Dark stellar clusters around Centaurus A are also believed to be remnants of a stripped dwarf (Bovill et al. 2016).

The purpose of this paper is to investigate how much DM can be left in the stripped stellar galactic nuclei that can be progenitors of massive GCs. To this end we run a set of simulations of dwarfs with different initial parameters on different orbits around the Milky Way (MW). We also calculate the J-Factor resulting from our final DM distribution and discuss whether or not the observed flux of gamma ray emission in $\omega$ Cen can be really explained by annihilation of DM gravitationally trapped by the GC.

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2 THE MODEL

2.1 Nucleated dwarfs orbiting the Galaxy

The present code for direct N-body simulations of nucleated dwarf galaxies is essentially the same as the one used in (Bekki & Tsujimoto 2015; BT16) in which the dynamical evolution of GCs in a dwarf galaxy orbiting the Galaxy is investigated. Since the details of the simulation code are given in BT16, we here briefly describe the code. It should be stressed here that the adopted code does not allow us to investigate how gas and star formation can control the evolution of interacting dwarfs and stellar nuclei which were investigated in our other works (e.g. Bekki 2007; Bekki & Chiba 2007; Bekki et al. 2019). The DM halo with the total mass of \( M_{\text{halo}} \) in a nucleated dwarf galaxy is represented by the ‘NFW’ one (Navarro et al. 1996) with a central cusp parameter \( (\rho_{\text{NFW}} = 4) \) and 100 kpc scale radius of \( R_{\text{NFW}} = 10 \) kpc.

In order to estimate the total mass and density of DM in the stripped stellar nuclei \( (R < 100 \text{ pc}) \) in a much better way, we here adopt the following setup for the dwarf’s DM halo: We first divide the DM halo into two regions with \( R \gg 100 \text{ pc} \) (‘outer’) and \( R < 100 \text{ pc} \) (‘inner’) and use a particle mass \( (m_{\text{dm}}) \) of only 0.02 times that of the outer particles and a factor 50 shorter time step width \( (\Delta t) \) for the inner halo. The details of this new method will be discussed extensively in Bekki et al. (2020). Here, we investigate models (labelled as S1 etc) in which \( m_{\text{dm}} = 200 \text{ M}_\odot \) and \( \Delta t = 10^4 \text{ yr} \) were adopted for the inner halo, so that we can resolve the inner 10pc-scale dynamical evolution of nucleated dwarf galaxies.

The nucleated dwarf is assumed to be as a bulge-less disk galaxy with the total stellar mass of \( M_s \) and the size of \( R_s \). The radial \( (R) \) and vertical \( (Z) \) density profiles of the stellar disk are assumed to be proportional to \( \exp(-R/R_0) \) with scale length \( R_0 = 0.2R_s \) and to \( \tanh^2(Z/Z_0) \) with scale length \( Z_0 = 0.04R_s \), respectively. The initial radial and azimuthal velocity dispersions are assigned to the disc component according to the epicyclic theory with Toomre’s parameter \( Q = 1.5 \). The stellar disk is assumed to have a stellar nucleus with a mass of \( M_{\text{nuc}} \) and a 5× scale radius of \( R_{\text{nuc}} \).

The nucleus is represented by a Plummer model with the free parameters \( M_{\text{nuc}} \) and \( R_{\text{nuc}} \). Our dwarf galaxy models have \( M_{\text{dm}} = 10^4 \text{ M}_\odot \), \( M_s = 1.2 \times 10^9 \text{ M}_\odot \), \( R_s = 1.3 \text{ kpc} \) and mostly \( M_{\text{dm}} = 10^7 \text{ M}_\odot \) and \( R_{\text{nuc}} = 30 \text{ pc} \), which is reasonable for the formation of massive GCs from nucleated dwarfs (e.g. BF03; Bekki & Yong 2012). The mass resolution (and softening lengths) of the disk and stellar nucleus are 1200 (18.4) and 1000 M\(_\odot\) (0.3 pc) respectively.

2.2 The Milky Way model

We investigated the “young” MW models rather than the “present-day” ones (BT16) to discuss the formation of massive GCs from stripped nuclei of dwarfs. The Galaxy in the present MW models is assumed to have a fixed three-component gravitational potential and the following logarithmic DM halo potential is adopted for the Galaxy,

\[
\Phi_{\text{halo}} = v_{\text{halo}}^2 \log(r^2 + d^2),
\]

where \( d = 12 \text{ kpc} \), \( v_{\text{halo}} = 93 \text{ km s}^{-1} \) (instead of 131.5 km s\(^{-1}\) suitable for the present-day Galaxy) and \( r \) is the distance from the center of the Galaxy. The gravitational potential of the Galactic disk is represented by a Miyamoto-Nagai potential (Miyamoto & Nagai 1975):

\[
\Phi_{\text{disk}} = -\frac{GM_{\text{disk}}}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}},
\]
where \( M_{\text{disk}} = 1.0 \times 10^{10} M_\odot \) (instead of \( 1.0 \times 10^{11} M_\odot \) for the present-day Galaxy), and \( x = 6.5 \) kpc, \( b = 0.26 \) kpc, and \( R = \sqrt{x^2 + y^2} \). The following spherical Hernquist (1990) model is adopted for the potential of the Galactic bulge:

\[
\Phi_{\text{bulge}} = -\frac{GM_{\text{bulge}}}{r + c},
\]

where \( M_{\text{bulge}} = 3.4 \times 10^9 M_\odot \), and \( c = 0.7 \) kpc.

To investigate how much DM can be left in the stripped nucleus, we take the following steps: First we evolve the dwarf through relaxation only (no tidal field) for 1.41 Gyr, then we expose the dwarf to the tidal field of the young MW, where it is stripped. We investigate dwarfs with different initial orbital velocities, dwarf positions, \( M_{\text{nuc}} \), and DM properties of dwarf galaxies. The orbits of the dwarfs with respect to the Galactic disk have an inclination of 30 or 60 degrees, and the stellar disks are inclined by 45 degrees with respect to the orbital planes. Although we mainly investigate “standard” models (labelled as “S”) with \( R_{\text{vir}} = 17.9 \) kpc and \( c = 16 \) for DM, we also investigate “low-density” models (“L”) with \( R_{\text{vir}} = 17.9 \) kpc and \( c = 8 \). Furthermore, we investigate model S11,0 with a GC a 200 pc outside of the dwarf’s centre of mass (COM) and several models with a GC 500 pc away from the COM. We will add an “O” to the label of those models.

2.3 Estimation of \( \gamma \)-ray flux from DM annihilation in stripped nuclei

Based on the mass and the density of DM in a stripped nucleus, we estimate the expected \( \gamma \)-ray emission stemmed from DM annihilation using the CLUMPY code (Hutter et al. 2019). To this end, we calculate the J-factor which is the integral of the squared DM density along a line of sight over the cone with a solid angle \( \Delta \Omega \):

\[
J(\Delta \Omega) = \int \Delta \Omega \int_{\text{l.o.s.}} d\ell \rho_{\text{DM}}^2(r(\ell, \Omega)),
\]

where \( \ell \) is the line of sight coordinate. Under the spherical symmetry assumption, we can rewrite \( \Delta \Omega \) as \( \Delta \Omega = 2\pi \sin \theta d\theta \), where \( \theta \) is the angular radius from the center of the object, and \( r(\ell, \Omega) = \sqrt{\ell^2 + d^2 - 2d\cos \theta} \), where \( d \) is the distance from the Sun (\( d = 5.4 \) kpc for \( \omega \) Cen). Taking the value of \( \rho_{\text{DM}} \) listed in the last column of Table 1, we perform the integration over an angular radius \( \Delta \Omega = 0.7^\circ \). For the estimation of the \( \gamma \)-ray energy spectrum, we adopt DM particle mass \( m_{\text{DM}} = 31.4 \) GeV estimated by Brown et al. (2019) and the velocity-averaged annihilation cross-section log\( 10(<\sigma v>) = -27.3 \) [cm\(^3\)s\(^{-1}\)], which is consistent with the upper limit on the cross section derived from a stacked analysis of dwarf spheroidal galaxies by Fermi-LAT data (e.g. Ackermann et al. 2013; Hayashi et al. 2016). We will use the following definitions: \( F_{\text{DM}} = \frac{\rho_{\text{DM}}^2}{m_{\text{DM}}} \) and \( F_s = \frac{\rho_{\text{nuc}}^2}{M_{\text{nuc}}} \), and consider nuclei with \( F_s(R < 30 \) pc) < 0.1 to be stripped.

3 RESULTS

Fig. 1 shows how the radial density profiles of DM, stellar disk, and nucleus evolve with time during tidal disintegration of the dwarf in the model S1 with \( M_{\text{nuc}} = 1 \times 10^7 M_\odot \) and \( R_{\text{peri}} = 2 \) kpc. In this model we saw a strong decrease of \( F_s(R < 30 \) pc) from \( 4.9 \times 10^{-2} \) to 0.0 within the first 2.82 Gyr. However, if we look at the stellar density of the disk between 40 and 50 pc, we notice that it is only \( 10^{-2} M_\odot\)pc\(^{-3}\). With this we would expect only 0.9 stars within the central 40 pc. Therefore, the sudden cutoff is likely to be caused by the low mass resolution. Nevertheless, this nucleus is considered stripped, according to our definition. The DM is dynamically relaxed under the presence of the disk in isolation for 1 Gyr (before the dwarf model is run). The flattened profile seen in the upper plane is due to this dynamical evolution consistent with Pasetto et al. (2010) and Oh et al. (2015). Meanwhile, \( F_{\text{DM}}(R < 30 \) pc) decreased from 1.63 \times 10^{-2} to 1.54 \times 10^{-2} and to 1.12 \times 10^{-2} during the following 2.82 Gyr. The absolute DM density within 30 pc decreases from 2.57 to 1.66 \( M_\odot\)pc\(^{-3}\) and \( F_{\text{DM}}(R < 100 \) pc) decreases from 0.50 to
be seen in Table 1. One result is that the DM density around the nucleus is smaller for models with a smaller pericentre. This is due to the tidal forces being stronger closer to the centre of the MW. In S5 tidal stripping is weaker, because of its large \( R_{\text{ini}} \). Theoretically we would expect that heavier nuclei are able to retain more DM. While no such correlation could be found, we cannot exclude it due to our small number of models. Apart from models S11,0 and S15,0 the models all show a higher average DM density within the inner 30 pc then within a 100 pc radius around the COM. This points to there still being non-stripped DM in the nucleus.

The two low-density models L8 and L10, with smaller NFW c parameter (= 8), show a significantly lower final DM density \( (R < 30 \text{ pc}) \) than the standard model, with \( c = 16 \) but otherwise similar parameters. This implies that there is a dependency between the initial and the final DM density. In most of the models with off-centre GCs disk stars and DM are stripped rapidly. This leads to a DM density of less then 0.2 \( M_\odot \text{pc}^{-3} \) within the central 30 pc and only a few hundredths of \( M_\odot \text{pc}^{-3} \) within the central 100 pc after 2.82 Gyr. This result can be understood easiest by viewing the nucleus as being stripped from the galaxy due to its large distance from the dwarf’s COM and the lack of time for it to spiral in due to dynamic friction. In S16,0, the massive GC can spiral into the central region before the disintegration of its host dwarf, because the pericenter is quiet large and thus tidal stripping is significantly weaker.

Fig. 3 shows a comparison of the DM densities at two different times. Most of the points are below the identity which means that models in general lose DM slowly due to tidal stripping during the long term dynamical evolution of the nuclei. Again we can see that the models with an off-centre GC instead of a nucleus have on average far less DM than the other models. The exception to this is again S16,0 which is visible as the green point at 0.3.

Fig. 4 shows the \( \gamma \)-ray energy spectrum calculated from DM annihilation via the \( bb \) channel in the case of model S1. In this case, the estimated J-factor value is \( J(0.7\,\text{GeV}) = 1.78 \times 10^{22} \text{ GeV}^2 \text{ cm}^{-2} \). Comparing with the observed energy flux of \( \omega \) Cen based on Fermi-LAT data (visible as dots in the Fig. 4) [Brown et al. 2019] [The Fermi-LAT collaboration 2019], S1 can explain the observed \( \gamma \)-ray emissions from DM annihilation. To estimate the size and mass we choose a cutoff density of \( 10\, M_\odot \text{pc}^{-3} \). This gives us a radius of 30 pc and a mass of \( 6.8 \times 10^5 \, M_\odot \text{pc}^{-3} \). This mass is a little below the highest estimate found in literature for \( \omega \) Cen’s mass of 7.13 \( \times 10^6 \, M_\odot \) [Richer et al. 1991]. However, other sources give significantly lower values i.e. \( 4.55 \times 10^5 \, M_\odot \) [D’Souza & Rix 2013]. Additionally, the small pericenter distance of S1 is consistent with corresponding observations.

Although S2 shows a high central density of DM in the GC, its \( R_{\text{peri}} \) is too large for \( \omega \) Cen. This could be a good model for the outer Galactic GCs with DM. S6, S7, and S9 also shows high DM densities \( \approx 1.5 \, M_\odot \text{pc}^{-3} \) within 30 pc and \( \approx 0.2 \, M_\odot \text{pc}^{-3} \) within 100 pc and small \( R_{\text{peri}} \) so that they can be the reasonable model for \( \omega \) Cen.

However, not all of the present models show the required high-density DM within the GCs, because the final DM densities within the central 30 pc depend on the model parameters. For example, S4, which has a low \( M_{\text{nuc}} \), shows \( \rho_{\text{ini}} \) of 0.19 \( M_\odot \text{pc}^{-3} \), which means that the \( \gamma \)-ray emission from DM annihilation should be too weak owing to the de-

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**Figure 3.** The average DM density \( (M_\odot \text{pc}^{-3}) \) within the inner 100 pc at \( T = 5.64 \text{ Gyr} \) over the DM density at \( T = 2.82 \text{ Gyr} \). The identity is shown in grey.

**Figure 4.** The \( \gamma \)-ray spectrum of simulated data from model S1 (red line) and compared to observations of \( \omega \) Cen (black dots). The observational data is taken from Brown et al. [2019] who integrated the data from The Fermi-LAT collaboration [2019] over 10 years.
pendsence of the emission flux on the DM density squared. Similarly, the low density models and the models with an off-centre GC instead of a nucleus show a very low final DM density. Thus, the large range of the DM densities in simulated massive GCs suggests that (i) the observed fluxes of gamma ray emission from 47 Tuc and ω Cen could be possibly explained by GC formation from stripped nuclei but (ii) it is also possible that the DM density in GCs is not high enough to reproduce the observed γ-ray emission if they originate from dwarfs with lower DM densities.

4 DISCUSSION AND CONCLUSION

We have shown that massive GCs like ω Cen can still contain a significant amount of DM, if they originate from nuclei of massive dwarf galaxies. Also we have shown that GCs formed well outside the central regions of their host dwarfs can have no DM after they are stripped from the host, even if they are massive at their birth. We therefore suggest that the formation sites of GCs in their hosts rather than their original masses can determine whether they can contain DM thus be sources of γ-ray emission from DM annihilation.

A number of the Galactic GCs are observed to have large stellar halos (e.g. Carraro et al. 2007, Olszewski et al. 2009), and recent numerical simulations have shown that these stellar halos can be explained, if the GCs are stripped nuclei of defunct dwarf galaxies (Bekki & Yong 2012). These previous studies combined with the present results therefore suggest that there can be other possible candidates of GCs with DM. On the other hand, Baumgardt et al. (2009) found no evidence for the presence of substantial DM in NGC2419. How common DM is in GC remains, therefore, up for debate. Since these clusters are not so close to us, the future Cherenkov Telescope Array will be ideal to detect the γ-ray signals of DM annihilation from these clusters.

Although we have demonstrated that the observed γ-ray flux in ω Cen is consistent with the threshing formation scenario, it is yet to be determined whether the gamma-ray observation can be explained better by DM annihilation or by milli-second pulsars. One way to distinguish between the two competing scenario is to observe ω Cen in radio wavelengths (e.g. Brown et al. 2019). It is thus our future study to investigate the expected radio properties of massive GCs with a significant amount of DM like ω Cen based on our dynamical models.

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