 Orbital Decay of Globular Clusters in the Galaxy with Little Dark Matter

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Abstract

Recently, van Dokkum et al. presented an important discovery of an ultra-diffuse galaxy, NGC1052-DF2, with a dark matter content significantly less than predicted from its stellar mass alone. The analysis relies on measured radial velocities of 10 globular clusters (GCs), of estimated individual masses of a few $10^6 M_\odot$. This is about 1% of the inferred mass of NGC1052-DF2 of $2 \times 10^8 M_\odot$ within a half-light radius, $R_e = 2.2$ kpc. The large relative mass and the old age of these objects imply that they might be susceptible to orbital decay by dynamical friction. Using analytic estimates and N-body simulations of an isolated system matching the inferred mass profile of NGC1052-DF2, we show that the orbits of the most massive GCs should already have decayed on a timescale of a few Gyrs. These findings should help in constraining mass profile and formation scenarios of NGC1052-DF2.

Key words: cosmology: theory – dark matter – galaxies: halos

1. Introduction

Small galaxies with shallow potential wells are an interesting probe of the nature of dark matter (DM). The sheer existence of DM in these objects has long ago allowed a constraint on the mass of neutrinos as candidates for DM (Tremaine & Gunn 1979). Further, their observed abundance is sensitive to both the power spectrum of the initial mass fluctuations (Lovell et al. 2013) and energetic feedback associated with star formation and supernovae feedback (Pontzen & Governato 2012). The ratio of DM to stellar mass of these galaxies is $\gtrsim 100$ (Behroozi et al. 2010; Moster et al. 2013). Therefore, the discovery of the galaxy NGC1052-DF2, with very little or no DM content at all, is particularly intriguing (van Dokkum et al. 2018b). A DM deficiency in NGC1052-DF2, in conjunction with the low acceleration, can in principle constrain modifications to Newtonian dynamics (e.g., Famaey et al. 2018; Moffat & Toth 2018; van Dokkum et al. 2018b). A lack of DM could serve as an indication of dark sector breaking of the equivalence principle and a violation of Lorentz invariance (e.g., Frieman & Gradwohl 1991; Kesden & Kamionkowski 2006; Keselman et al. 2009; Bettoni et al. 2017). Indeed, an additional fifth force in the dark sector could completely segregate the stellar and DM components due to the gravitational force field of a more massive host, such as the large elliptical NDF1052 in the vicinity of NGC1052-DF2.

The analysis of NGC1052-DF2 is based on the measured radial velocities of 10 compact objects that are similar to galactic globular clusters (GCs) and were hence termed so by van Dokkum et al. (2018b). The 90% confidence limit on the line-of-sight velocity dispersion of these objects is estimated as $\sigma < 10.5$ km s$^{-1}$ (van Dokkum et al. 2018b). Martin et al. (2018) have argued that the small number of tracers used to constrain the kinematics of the galaxy could be associated with poorly determined velocity dispersion, and hence is the cause of the apparent lack of DM.

The GCs in NGC1052-DF2 are much more luminous than typical GCs with the brightest of them, GC-73, having an absolute luminosity and metallicity similar to $\omega$ Cen (van Dokkum et al. 2018a), the brightest GC in the Milky Way. We infer the mass of GC-73 to be $\sim 3.5 - 4 \times 10^6 M_\odot$, the close to that of $\omega$ Cen (D’Souza & Rix 2013). The second brightest object, GC-77, is consequently only a factor of 1.6 less massive. Thus the mass one of the brightest GCs is about 1% of the high-end mass estimate of NGC1052-DF2, as provided by van Dokkum et al. (2018b). This makes these objects particularly susceptible to dynamical friction (Chandrasekhar 1949). The timescale for orbital decay of a GC of mass $M_{GC}$ in a galaxy with mass profile $M_{gal}(r)$ is (Binney & Tremaine 2008)

$$t_{DF} = \frac{1.17 M_{gal}(r)}{\ln \Lambda} M_{GC} t_{\text{cross}}.$$  (1)

The derivation of this relation employs several assumptions about the structure of the galaxy that do not necessarily hold in reality (c.f., Binney & Tremaine 2008; Arca-Sedda & Capuzzo-Dolcetta 2016, for details). Therefore, we use it to infer a rough estimate only. Consider an object at a 2 kpc distance from the center and with a velocity of 5 km s$^{-1}$. Then, $t_{\text{cross}} \approx 2$ kpc/5 km s$^{-1} \approx 0.4$ Gyr. If the mass ratio is $\approx 100$ and $\ln \Lambda \approx 6$, we find $t_{DF} \lesssim 8$ Gyr. Given that the estimated age of the GC is $\gtrsim 9$ Gyr (van Dokkum et al. 2018a), orbit decay by dynamical friction (DF) should be taken into account.

In the remainder of the Letter, we provide a more robust assessment of the effects of DF using N-body simulations designed to model the NGC1052-DF2 system.

2. Simulations

We study the orbital decay using N-body simulations of an isolated collisionless system with a density profile matching the general features of NGC1052-DF2, as reported in van Dokkum et al. (2018b). We model the galaxy as a two-component system of stars and DM, both assumed spherical with respect (Einasto & Haud 1989) density profiles. The observed two-dimensional (2D) structure of the galaxy is represented by van Dokkum et al. (2018b) in terms of a Sérsic profile with index $n_S = 0.6$ and half-light radius $R_e \approx 2.2$ kpc. We have found that this is very well approximated as a projection of the three-dimensional (3D) Einasto density profile with parameters $r_e = 10$ kpc, $r_{25} = r_e/8.1$ and $n_E = 2.5$. The total mass in stars is normalized to $2 \times 10^8 M_\odot$, as in the observations. The stellar component is assumed to be...
embedded in a DM halo with an Einasto profile with parameters derived from halos identified in large high-resolution cosmological simulations (e.g., Ludlow et al. 2013). We consider halos of virial masses $10^8 M_\odot$ and $10^7 M_\odot$ corresponding to virial radii $r_v = 10$ kpc and $r_v = 21.6$ kpc, respectively. For both masses we fix the Einasto parameters at $r_\epsilon = r_v/20$ and $n_E = 6$. van Dokkum et al. (2018b) derived the constraints on the mass profile, taking a distance of 20 Mpc for NGC1052-DF2. There is, however, a debate regarding the distance. Trujillo et al. (2018) have presented arguments that the galaxy may be much nearer at a distance of $D = 13$ Mpc. van Dokkum et al. (2018c) countered these arguments, producing a revised distance of $19 \pm 1.7$ Mpc. Nonetheless, here we also model GC orbits for parameters appropriate for $D = 13$ Mpc, where the spatial extent of the galaxy is reduced to $R_t \approx 1.4$ kpc and its stellar mass to $6 \times 10^7 M_\odot$. Further, we model the stellar component as an Einasto profile with the same $r_\epsilon$ and $n_E$ as above, but with $R_{\epsilon,2} = r_v/12.1$ and mass normalized to $6 \times 10^7 M_\odot$. The parameters of the DM halo remain as before, with a virial mass of $10^9 M_\odot$, consistent with Trujillo et al. (2018).

The simulations are run using the publicly available treecode written by J. Barnes (Barnes & Hut 1986), with a force softening $\epsilon = 0.05$ kpc and an opening angle criteria $\theta = 1$ rad. This value for $\epsilon$ is close to $b_{\min} \approx G M_{GC}/V_{GC}^2$, the impact parameter above which encounters between the GC and galactic particles are important for DF (Binney & Tremaine 2008). Approximating the speed of GC by $V_{GC}^2 \approx G M_{gal}/R_{gal}$, we find $b_{\min} \approx R_{gal} M_{GC}/M_{gal} \approx 0.1$ kpc for $R_{gal} \approx 10$ kpc and $M_{GC}/M_{gal} \approx 0.01$. In any case, the uncertainty in fixing $\epsilon$ is of minor significance relative to the the unknown detailed structure of the galaxy and the actual 3D positions of the GCs in the observations. Each simulation contains $2.4 \times 10^5$ particles of equal mass, representing the galaxy without the GCs. A particle at position $r$ from the center is assigned a randomly oriented initial velocity with a magnitude equal to the circular velocity, $V_c = \sqrt{GM(<r)/r}$, where $M(<r)$ is the total (stars + DM) within $r$. The initial configurations are evolved using the treecode for 1.5 Gyr to obtain the corresponding relaxed configurations. Figure 1 shows the 2D mass profiles obtained from the simulation runs without GCs, for two halo masses, $10^8 M_\odot$ and $10^7 M_\odot$, as indicated in the figure. The evolved mass profiles are actually close to the respective profiles obtained from the initial conditions. The stellar component in both simulation runs should match the observed stellar profile. Indeed, stellar distributions represented by the orange (solid and dashed) curves for the low- and high-mass simulations, match very well the corresponding profile in Figure 4(a) in van Dokkum et al. (2018b). In computing the 2D DM profiles, we excise particles with (3D) distances larger than 10 kpc in the simulations. We obtain a good match with the DM mass profiles shown in the same figure of van Dokkum et al. (2018b). The arrows represent the 90% confidence limits on the mass estimates from the observations (van Dokkum et al. 2018b). The low-mass profile is close to the 90% mass limits from the observations. The circular velocity, $\sqrt{GM(<r)/r}$, for the lower-mass profile in the simulation, reaches a maximum of $\sim 17$ km s$^{-1}$ at $r = 1–2$ kpc and declines slowly at larger radii. The corresponding line-of-sight velocity dispersion is $\sim 9.8$ km s$^{-1}$, consistent with the observations. We have also checked (but do not show) that the simulated profiles corresponding to a distance $D = 13$ Mpc of NGC1052-DF2 agree well with Trujillo et al. (2018). Once a relaxed state is reached, a massive particle representing a GC is placed in each simulation galaxy. For van Dokkum et al. (2018b) GCs of masses 1, 2, 3, and 4 million solar masses are placed at various distances from the center with orbital eccentricity of $e \approx 0.5$ (e.g., Benson 2005; Wetzel 2011). The observed NGC1052-DF2 is expected to be truncated at $R_c \gtrsim 7$ kpc by the tidal gravitational force field of NGC 1052, a much larger nearby elliptical galaxy at a projected distance of $\sim 100$ kpc. Therefore, we only consider GC particles within $R_c$.

After the inclusion of GCs, the simulations are run forward for 10 Gyr, with an energy conservation to better than 1%. For each simulated galaxy, a “center” is identified as the particle with the lowest potential energy. Distances of GC particles are computed relative to the center in the corresponding simulation. Figure 2 is a summary of the results for GCs distances versus time in the lower-mass galaxy. The results are not reliable numerically for distances close to the softening parameter, $\epsilon$, e.g., at a distance of $4\epsilon = 0.2$ kpc force bias introduced by the Plummer smoothing is about 10%. For the low-mass galaxy run (top panel), the orbit of the GC particle with $M_{GC} = 3 \times 10^5 M_\odot$ (cyan line) decays within 6 Gyr for an initial apocenter as large as 6 kpc. Starting from an apocenter of 4 kpc, the same curve shows that the orbit decays within 4 Gyr. For an initial apocenter of $\lesssim 2$ kpc, orbits decay on a much shorter timescale of less than 3 Gyr, even for the lightest particles. At a 20 Mpc distance, the brightest observed GC has a mass in between the two largest GC particles and lies at a projected separation $\lesssim 2.4$ kpc. The second brightest observed cluster is $\sim 2–2.5 \times 10^5 M_\odot$ at a projected separation of 0.4 kpc. The middle panel represents orbits in the simulations of a galaxy with a halo that is 10 times more massive, still at a 20 Mpc distance. Orbital decay is clearly slower; however, it remains significant. Tracing the red curve, a GC with a

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1 Given a projected distance $R$, the probability for a 3D distance $r$ is $P(r) = P(\geq r) \times \frac{1}{r} \frac{1}{r}$ for $R < R_e$, where $R_e$ is the truncation radius of the galaxy. This assumes that the number density of GCs falls like $1/r$. 

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Figure 1. Mass profiles from the simulations run without GCs at an output time $t = 1.5$ Gyr. The lower curve represents a low-mass galaxy close to the observed 90% mass limits as indicated by the arrows. The upper curve is obtained from a simulation with four times the mass in the lower curve.
$3 \times 10^6 M_\odot$ starting at an apocenter of 4 kpc sinks to the center at $\lesssim 5$ Gyr. According to the green curve, a particle with $2 \times 10^6 M_\odot$ (close to the mass of the second brightest observed GC), starting with apocenters of 3 and 2 kpc reaches the center after $\sim 4$ Gyr and $\sim 2$ Gyr, respectively. Note that the orbit of a $2 \times 10^6 M_\odot$ particle starting from 3 kpc decays over the same timescale in the low- and high-mass galaxies. This is seen by comparing the black curve in the top panel with the green curve in the middle panel. Results for simulations corresponding to a galaxy at a 13 Mpc distance are represented in the bottom panel. On account of the different assumed distances to NGC1052-DF2, the GC masses in the simulations corresponding to Trujillo et al. (2018) are smaller than those for van Dokkum et al. (2018b). This boosts the dynamical friction timescale, but we must bear in mind that the lower distance implies smaller separations between the GCs and the center of NGC1052-DF2. At a 13 Mpc distance, the mass of the brightest GC is $\approx 1.5 \times 10^6 M_\odot$. Because whole system is now less extended, we consider smaller separations than before. Starting from a 3 kpc, a $2 \times 10^6 M_\odot$ particle reaches the center within $\lesssim 2.5$ Gyr, faster than in the top and middle panel. The reason is the smaller stellar mass in the 13 Mpc distance galaxy, which results in an overall less mass than the 20 Mpc case, within the relevant radius. Therefore, along with the lower distance to NGC1052-DF2, dynamical friction is expected to play an important role.

3. Discussion and Conclusions

We have argued that DF is an important process in NGC1052-DF2 for the mass range reported in van Dokkum et al. (2018b). Our findings imply that the presence of the observed massive GCs at distances $\lesssim 6$ kpc is likely inconsistent with the reported mass estimate of NGC1052-DF2. We have seen that a boost of the galaxy mass by a factor of 4 to $\gtrsim 10^9 M_\odot$ is insufficient to suppress the effects of DF on the largest GCs in the relevant range of distances from the center. The scaling with $M_{\text{gal}}$ implies that boosting the total mass of the galaxy by a factor of a 100, as would be expected for a typical galaxy the same stellar mass, practically eliminates the effects of DF. However, an order of magnitude increase over the reported mass limit in van Dokkum et al. (2018b) is sufficient to increase to $t_{\text{DF}} \gtrsim 10$ Gyr. Thus, although our findings indicate that the ratio of DM to stellar mass in NGC1052-DF2 should be on the order of a few tens, they do not strictly require the typical high value of a few hundreds expected from its stellar mass. A more detailed analysis of the mass constraints implied by the measured GC velocities might still yield the result that the dynamical mass might be large enough to avoid short dynamical friction timescales.

Another way out is if the system is relatively young. But this possibility has yet to be demonstrated in a physical scenario that will yield consistency with all observations of the system (van Dokkum et al. 2018b). We have also run simulations where the whole system is subject to the external field of a nearby larger galaxy like NGC 1052 in the vicinity of NGC1052-DF2. The results regarding the orbital decay of GCs are unaltered by the inclusion of a (static) external field, provided that they lie within the tidal radius of the simulated NGC1052-DF2. It should be pointed out that the relative radial velocity of NGC1052-DF2 relative to NGC 1052 is 293 km s$^{-1}$ (van Dokkum et al. 2018b), while line-of-sight velocity dispersion of the NGC 1052 group is only 110 km s$^{-1}$ (van Dokkum et al. 2018b), which is consistent with the circular velocity of 200 km s$^{-1}$ measured from the H I content of NGC 1052 Gorkom1986. Thus the relative speed of NGC1052-DF2 is close to the escape velocity from NGC 1052. At a projected distance of 100 kpc between the two galaxies, NGC1052-DF2 is likely to be just skimming past NGC 1052. Nonetheless, even with tests where the external field generated from a galaxy with a one-dimensional (1D) velocity dispersion of 300 km s$^{-1}$, the GCs either sink to the center or completely stripped (for large initial separations).

Ogiya & Go (2018) have shown that if (i) NGC1052-DF2 is initially harbored in a $4.9 \times 10^{10} M_\odot$ halo with a large core and (ii) is on a highly radial orbits in the field of NGC 1052, then gravitational tidal stripping could produce mass profiles consistent with the observations. As argued Ogiya & Go (2018), this set up is unlikely and systems like NGC1052-DF2 are expected to be rare. As mentioned above, we argue the relative speed between NGC1052-DF2 and NGC 1052 makes...
this set up unrealistic. Thus, tidal stripping scenarios (e.g., Di Cintio et al. 2017; Carleton et al. 2018) are unlikely to apply in the case of NGC1052-DF2.

The situation is reminiscent of Fornax, the most massive satellite of the Milky Way. Fornax is the only satellite of the Galaxy containing GCs; there are five of them, and they are observed at projected distances \( \sim 1 \) kpc from its center. The DF timescale is short, and at least the two most massive of the GCs should have reached the center within a few Gyr. Fornax is DM dominated with a halo mass of \( \sim 1.5 \times 10^{12} M_\odot \), close to the mass of NGC1052-DF2 as given in van Dokkum et al. (2018b).

But there are distinct differences between the two systems. Fornax is much less spatially extended than the ultra-diffuse NGC1052-DF2 if indeed at a distance of \( D = 13 \) Mpc. Further, the massive GC that Fornax harbors is less that \( 0.3\% \) of its mass. Therefore, none of our simulations corresponding to 20 Mpc can be directly associated with the relevant DF calculation done for Fornax. At \( D = 13 \) Mpc, the NGC1052-DF2 system becomes much more akin to Fornax. The larger GC mass in NGC1052-DF2 could make dynamical friction more problematic than in Fornax, but the tidal radius of Fornax is better determined and we have less freedom in fixing the 3D separation. Several ways out have been suggested to solve the Fornax mystery, such as having a core of constant density within \( \sim 1 \) kpc (Goerdt et al. 2006). This cored density profile, however, is very hard to achieve within the context of viable warm DM models (MacCio et al. 2012). Further, even a mild cusp would bring the orbits of some of the GCs to decay (Cole et al. 2012). Other solutions suggest that the Fornax has only recently captured its GCs and that they are located near its tidal radius (Oh et al. 2000; Angus & Diaferio 2009; Cole et al. 2012). This set up could be relevant for NGC1052-DF2, but it seems unlikely and its feasibility is hard to assess.

The orbit calculations done in this Letter should serve as a general indication for the orbital decay times. The unknown detailed structure of the NGC1052-DF2, and the availability of only partial phase space coordinates of the GC system, prevent an accurate determination of the orbits. Nonetheless, the variety of numerical experiments presented here, sustained by analytic estimation, demonstrate clearly that typical decay timescales could be comfortably shorter than the age of the system. A clear conclusion from our work is that any mass model and formation scenario for NGC1052-DF2 should consider the constraints on GC orbital decay by DF. This statement is valid for the two distance measurements reported for this galaxy. A full assessment of the parameter space of plausible mass profiles and orbital characteristics, similar to the analysis Cole et al. (2012) for Fornax, could be worthwhile. However, an extensive investigation is beyond the scope of this Letter.

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