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Dwarf Spheroidal Galaxies and Dark Matter
Leo IV and Leo V: A bound pair?

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The dwarf spheroidal (dSph) galaxies are though to be the most dark matter dominated objects known. Leo IV and Leo V are two ultra-faint dwarf spheroidal galaxies recently found around the Milky Way. Their distances to the Milky Way are 154kpc and 175kpc respectively. The rather short difference in radial distance and the fact that they also have a small projected distance on the sky led to the idea that we might see a new pair of gravitationally bound galaxies - like the Magellanic Clouds. Our results show that the minimum total dark matter mass required for the pair to be bound has to be between $1.6 \times 10^{10} M_{\odot}$ and $5.4 \times 10^{10} M_{\odot}$ (within the virial radius). Computing the mass of dark matter within the standard optical radius of 300pc shows that our models are within the predicted range of dark matter content for satellites so faint. We therefore conclude that it could be possible that the two galaxies constitute a bound pair.

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1. Introduction

Many new faint dwarf spheroidal (dSph) galaxies have been discover around the Milky Way (MW) (e.g. Willman et al., 2005; Zucker et al., 2006; and many more). Many of those dwarfs are less luminous than star clusters and their stars exhibit high velocity dispersions (e.g. Simon & Geha, 2007). If these objects are in virial equilibrium then their luminous masses do not explain their high velocity dispersion, and this would imply that these objects are the most dark matter (DM) dominated objects known in the universe. They would exhibit high mass-to-light (M/L) ratios, in the order of hundreds (e.g. Simon & Geha, 2007) or even thousends for some cases. In this paper we focus on two of these new ultra-faint dwarfs, namely Leo IV (Belokurov et al., 2007) and Leo V (Belokurov et al., 2008). Their properties are studied by many authors: for Leo IV: (Moretti et al., 2009; Simon et al., 2010; Sand et al., 2010) and for Leo V: (Walker et al., 2009a,b). Both galaxies are very close to each other in radial distance (22 kpc) (Moretti et al., 2009; De Jong et al., 2010) and also in projected distance on the sky. Their relative radial velocity differs only by about 50 $\mathrm{km\,s^{-1}}$. Already in the discovery paper of Leo V the authors speculate that the two dwarfs could form a bound pair similar to the Magellanic Clouds. De Jong et al. (2010) argued that to form a bound object the twin system would need a lot of DM, much more than it is seen in similar faint satellites. Nevertheless, the authors claimed that it is highly unlikely that the two satellites are a simple by-chance alignment. They also rule out the possibility that the two faint dwarfs are not galaxies at all but simple density enhancements of a stellar stream by orbital arguments. So they conclude that they might be a 'tumbling pair'. With our paper (see Blaña et al. 2012) we want to investigate the hypothesis of a bound pair further. Using a restricted N-body code we search for the minimal total mass the system needs, in order to form a tight bound pair.

2. Method

1 We adopt scenarios where we model the two galaxies as two dark matter haloes (DMH) orbiting each other. We ignore the luminous components of the galaxies, because their masses are too low to gravitationaly bound the pair, or to significantly affect their orbits.

2 To restrict the parameter space we adopt two mass-ratios between the two satellites. Using the measured absolute magnitudes, the luminosity ratio between Leo IV and Leo V is 1.8. In our simulations we adopt this ratio for the masses of the two DM haloes as well. We also use scenarios where the ratio is 1, that means that both haloes have the same mass.

3 We proposed two main scenarios for our models as follows:
3.1) *Only radial velocities*: We use only the measured radial velocities, which is the only known component. In the DMH scenario, we also require that the centre of the bigger halo (Leo IV) should not leave the smaller halo (Leo V). This ensures a tight bound pair.
3.2) *Radial and tangential velocities*: This scenario is the same as the previous one except that here we add to the galaxies a tangential velocity component to the respective radial velocities. The magnitude of them is as high as the respective radial component.
All DM halos are assumed to have a NFW profile and for each of the cases we vary the concentrations of the haloes in a range usually assumed for the dSph galaxies of $c = 5, 10, 20$.

4 We determine the minimum mass of the system to remain bound using a simple integration code to cover the huge parameter space (Tab.1).

5 Finally we verify the results with full N-body simulations (Tab.1).

In total our investigation produces twelve different solutions to the problem.

3. Results & Conclusion

In Tab.1 and Fig.1(*left panel*) the *total* DM mass for the two faint satellites is shown. Just by looking at our different cases we get results which differ by an order of magnitude in total mass. The values are very high and would put them amongst the most DM dominated objects known. Still these results do not infer that this scenario is impossible. We may see in the left panel of Fig. 1 that the *total* mass does not strongly depend on the concentration of the haloes nor in the mass-ratio between them. And it strongly varies depending on the velocity or kinetic energy they have (scenario with only radial velocity or scenario with radial and tangential velocity). We compare the masses and M/L-ratios of Leo IV with the values measured by Simon & Geha 2007 within an optical radius of 97pc ($M = 1.4 \pm 1.5 \times 10^6 M_\odot$ and $M/L_V = 78\,[M/L_V]_\odot$). Within the same radius, our models give masses between $5.92 \times 10^5 M_\odot$ and $6.19 \times 10^6 M_\odot$. Similarly, for the M/L-ratios we have a range of $33--344\,[M/L_V]_\odot$ respectively. We did the same for Leo V within a radius of 67.4pc with $M = 3.3^{+9.1}_{-2.5} \times 10^5 M_\odot$ and $M/L_V = 75^{+230}_{-58}\,[M/L_V]_\odot$ (Walker et al., 2009a) and we calculated with our models a mass range of $2.7 \times 10^5 M_\odot$ to $2.5 \times 10^6 M_\odot$ and a range of $27--250\,[M/L_V]_\odot$ for the M/L-ratios. Furthermore, we checked our results against the trend for dSph galaxies published by Wilkinson et al. (2006) (shown in Fig 1 and in Tab.2), where they calculate the M/L-ratios within a standard optical radius of 300 pc. Using the same radius, our simulations predict a range for the M/L-ratios $\log_{10} M/L_V = 2.5$–3.7 (See more details for each galaxy in Tab. 2). These values are extremely high but encompass the predictions for dSph galaxies that faint, if an extrapolation of the known values to the faint magnitudes of the Leos is used. The range of observational values allow us to exclude the models with highly concentrated DM haloes ($c = 20$).

The comparison between the results of the restricted and the full N-body simulations gives deviations of the distance criterion, but they do not change the outcome of the simulations as it is shown in the eighth column in Tab.1. This distance difference would imply an error in the masses of just 10 per cent and it would not it alter the inferred M/L-ratios significantly. Therefore it does not change our conclusion. A bound pair in the restricted case is still a bound pair in the full simulations.

Summing up, we conclude that the total mass we infer for the system of the Leos to be bound is in fact within a reasonable range of values. Therefore, it could be possible that the two galaxies form a bound pair, making them an ultra-faint counterpart of the Magellanic Clouds.

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Case	c	$M_{DM,LeoIV}$ $[M_\odot]$	$r_{vir,LeoIV}$ [kpc]	$M_{DM,LeoV}$ $[M_\odot]$	$r_{vir,LeoV}$ [kpc]	M_{tot} $[M_\odot]$	Ratio	Scenario
0a	—					4.18×10^{9}	–	Point masses (a)
0b	—					1.47×10^{10}	–	Point masses (b)
1	5	1.34×10^{10}	49.00	7.45×10^{9}	40.29	2.09×10^{10}	0.965	rad. vel. mass ratio 1.8
2	10	1.27×10^{10}	48.11	7.05×10^{9}	39.55	1.98×10^{10}	0.953	rad. vel. mass ratio 1.8
3	20	1.22×10^{10}	47.42	6.75×10^{9}	39.98	1.89×10^{10}	0.935	rad. vel. mass ratio 1.8
1a	5	9.05×10^{9}	42.99	9.05×10^{9}	42.99	1.81×10^{10}	1.179	rad. vel. equal mass
2a	10	8.55×10^{9}	42.18	8.55×10^{9}	42.18	1.71×10^{10}	1.194	rad. vel. equal mass
3a	20	8.30×10^{9}	41.76	8.30×10^{9}	41.76	1.66×10^{10}	1.204	rad. vel. equal mass
4	5	3.47×10^{10}	67.25	1.93×10^{10}	55.28	5.39×10^{10}	0.993	rad. & tang. vel. mass ratio 1.8
5	10	3.11×10^{10}	64.83	1.73×10^{10}	53.30	4.14×10^{10}	0.956	rad. & tang. vel. mass ratio 1.8
6	20	2.84×10^{10}	62.90	1.58×10^{10}	51.70	4.42×10^{10}	0.968	rad. & tang. vel. mass ratio 1.8
4a	5	2.40×10^{10}	59.50	2.40×10^{10}	59.50	4.80×10^{10}	1.450	rad. & tang. vel. equal mass
5a	10	2.20×10^{10}	57.80	2.20×10^{10}	57.80	4.40×10^{10}	1.375	rad. & tang. vel. equal mass
6a	20	2.10×10^{10}	56.91	2.10×10^{10}	56.91	4.20×10^{10}	1.284	rad. & tang. vel. equal mass

Table 1: The first column gives the number of the case, the second is the adopted concentration of the haloes. Then we give the mass of the DM halo and its virial radius for Leo IV and Leo V. The next column gives the total masses in DM of the whole system, the next column shows the "ratio" by which the maximum distance differs between the full N-body simulation and the two-body code. The last column is a short explanation for the cases rad. vel. = only radial velocity, rad. & tang. = radial and tangential velocity adopted; mass ratio 1.8 = the two haloes have a fixed mass ratio of 1.8; equal mass = the two haloes have the same mass.

Case	1	2	3	1a	2a	3a	4	5	6	4a	5a	6a
c	5	10	20	5	10	20	5	10	20	5	10	20
LeoIV: Log_{10} $(M_\odot/L_\odot)$	2.544	2.929	3.343	2.484	2.867	3.279	2.686	3.067	3.482	2.631	3.014	3.425
LeoV: Log_{10} $(M_\odot/L_\odot)$	2.710	3.092	3.499	2.740	3.122	3.534	2.853	3.232	3.641	2.886	3.270	3.688

Table 2: Mass-to-light ratios within a radius of 300 pc. **Note**: We adopt V-band magnitudes of -5.8 for Leo IV and -5.2 for Leo V.

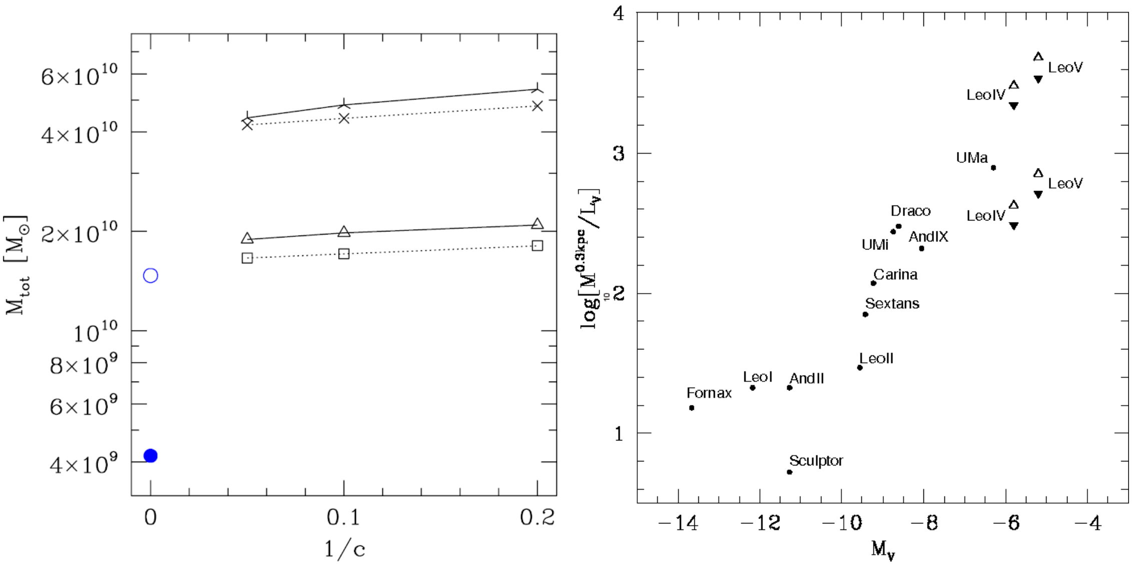

Figure 1: *Left:* Minimum DM mass of the total system M_{tot} versus concentration of the haloes. We plot $1/c$ in favour of c to include the point-mass results at $1/c = 0$ (cases 0a,b; plotted as open and filled circle - blue online). Solid lines are the results using the mass-ratio 1.8. Triangles are cases with radial velocity only and tri-stars with additional tangential velocity. Dashed lines show the results of equal mass haloes. Squares are radial-velocity-only cases and crosses have additional tangential velocity. *Right:* Mass-to-light ratios within a radius of 300 pc. The circles are dSph Galaxies of the Local Group as reported by Wilkinson et al. (2006). For Leo IV, the filled upside-down triangles are cases 1a and 3 (concentrations $c = 5$ and $c = 20$ respectively) with radial velocities only. The open triangles are cases 4a and 6 ($c = 5$ and $c = 20$) with radial and tangential velocities. For Leo V we plot the values of cases 1 and 3a as well as 4 and 6a, respectively. We use these specific cases because they span the whole range of our results.

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