Binary satellite galaxies

Jarah Evslin1,2,3★
1Institute of Modern Physics, CAS, NanChangLu 509, Lanzhou 730000, China
2TPCSF, IHEP, CAS, YaQuanLu 19B, Beijing 100049, China
3KEK Theory Center, Tsukuba, 305-0801, Japan

ABSTRACT

Suggestions have appeared in the literature that the following four pairs of Milky Way and Andromeda satellite galaxies are gravitationally bound: Draco and Ursa Minor, Leo IV and V, Andromeda I and III, and NGC 147 and 185. Assuming that a given pair is gravitationally bound, the Virial theorem provides a crude estimate of its total mass and so its instantaneous tidal radius. In the case of each pair except for Leo IV and Leo V, the estimated tidal radius is inferior to the separation between the two satellites, suggesting that these pairs are not currently gravitationally bound. Their proximities may be explained if each pair condensed from the remnants of a formerly gravitationally bound structure, but such a scenario is in tension with the absence of older pairs with a wider separation.

Key words: galaxies: dwarf – galaxies: kinematics and dynamics – Local Group.

1 INTRODUCTION

The phase space distribution of the satellite galaxies observed in our Local Group contains structures and correlations so far not seen in cold dark matter (ΛCDM) simulations, such as the great disc of Milky Way satellites (Kroupa, Theis & Boily 2005), the thin corotating disc of Andromeda (Ibata et al. 2013), the large planes of Pawlowski, Kroupa & Jerjen (2013) and, farther away, the filamentary structure around NGC 3109 (Bellazzini et al. 2013).

It also contains a number of associated pairs of satellite galaxies. In addition to the Magellanic clouds, van den Bergh (1998) suggested that Andromeda’s satellite galaxies NGC 147 and 185 may be gravitationally bound to each other and used this assertion to estimate their masses. The phase space proximity of Leo IV and V was observed by Belokurov et al. (2008) while de Jong et al. (2010) and Blana, Felthauer & Smith (2012) have suggested that this pair is bound and again used this conjecture to estimate their masses. Recently Fattahi et al. (2013) have identified two more pairs: And I and III and also Draco and Ursa Minor. They observed that this number of pairs greatly exceeds that found in simulations.

The fact that the number of pairs exceeds that in simulations is not necessarily in conflict with ΛCDM. It could simply be that the simulations have merger histories which differ from that of our Local Group (Belokurov 2013). In this case the existence of the pairs is important not because of what it teaches us about the properties of dark matter, but rather because of what it teaches us about our own history.

The purpose of the present note is to investigate two related questions: are these pairs gravitationally bound? Or if not, could each pair have condensed from a single progenitor?

The proper approach to these questions would be a many body simulation of the kind that has been performed extensively for the Magellanic Clouds. The problem with this approach is that, unlike the Magellanic clouds, the proper motions of these satellites are not known.1 This uncertainty exceeds the additional precision gained by a full simulation, and so until these motions are determined by the Gaia mission such simulations will be of limited use.

Therefore, following van den Bergh (1998), de Jong et al. (2010) and Blana et al. (2012) our approach will consist of crude calculations which will be reliable to within a factor of about 2. The Virial theorem yields an estimate of the satellite’s masses and so their tidal radii. We will find that in most cases the distance between two satellites in a pair exceeds this tidal radius and the pairs are not presently bound. We then turn to the possibility that the pairs were bound at one time and now are drifting apart. We find that the separations between pairs are all quite small, with no compelling candidates for intermediate separations. This suggests that all of the pairs became unbound within the past 2 billion years with no pairs unbinding earlier. While such a scenario presents no clear inconsistency, one may object that it is statistically unlikely.

1 As has been reviewed in Pawlowski & Kroupa (2013) the proper velocities of the pair Draco and Ursa Minor have been measured by several groups, but the results of the various groups are in much stronger disagreement than is indicated by their error bars and indeed the differences are of the same order as the transverse velocities themselves.
2 MASS ESTIMATES

In this section and the next we will present evidence that most of these pairs are not currently gravitationally bound. To do this, we begin by assuming that they are bound by Newtonian gravity. Let the two galaxies have masses \( M_1 \) and \( M_2 \) and speeds \( v_1 \) and \( v_2 \) in the centre of mass frame.

For now, we will consider each galaxy to be a point mass. The total kinetic and potential energies are

\[
T = \frac{1}{2} M_1 v_1^2 + \frac{1}{2} M_2 v_2^2 = \frac{v^2}{2} M_2, \quad U = -\frac{G M_1 M_2}{r}
\]

(1)

where \( M_1 = M_1 + M_2 \) and \( v = v_1 + v_2 \) are the total mass and relative speed, \( G \) is Newton’s constant and \( r \) is the distance separating the two galaxies. In principle \( U \) also contains a positive term (Tonnesen & Cen 2012) which incorporates the fact that the expansion of the universe tends to separate the two galaxies. Such a term would increase the masses that we will derive below; however for the small separations in the binary systems here the correction is negligible.

Of course, galaxies are not point masses. Nonetheless, Birkhoff’s theorem (Jebsen 1921) implies that the same formulas apply in the approximation in which they are spherically symmetric and have radii \( r < d \).

Assume that the system is gravitationally bound

\[
M_T > \frac{v^2 d}{2G_N}
\]

(2)

Generally, only the line-of-sight velocity is available. Let \( v_{los} \) be the difference between the line-of-sight velocities of the two galaxies in a pair. As \( v_1 \leq v_2 \) one may write a weaker inequality

\[
M_T > \frac{v_{los}^2 d}{2G_N} \geq M_{min} = \frac{v_{los}^2 d}{2G_N}
\]

(3)

Note that this bound applies to pointlike and to extended objects alike, if pair of extended objects violate this bound then either they will separate or they will disassemble into a part which separates and a part which remains.

A very rough estimate of the total mass may be obtained as follows. Isotropy yields an estimate of \( v = \sqrt{3} v_{los} \) for the 3D velocity, given an average line of sight direction, while the Virial theorem implies that \( 2T = -U \) at an average time and so

\[
M_T \sim \frac{v_{los}^2 d}{G_N} \sim \frac{3v_{los}^2 d}{G_N} = 6M_{min}
\]

(4)

This approach differs from that of Davis et al. (1995) in which only the projected distance is used as we do not assume that the vector separating the two galaxies is parallel to their relative velocity.

What if the galactic radii \( r > d \)? Strictly speaking it makes little sense to discuss \( r > d \) since a particle whose distance \( r \) from a given galactic centre exceeds the distance \( d \) between the centres of the galaxies is gravitationally associated with the pair of galaxies, not with just one member of the pair. So the case \( r > d \) corresponds to an extended subhalo, of radius greater than \( d \), which contains two overdensities which are identified as the two galaxies in the pair.

In this more generalized context, what can one say about the mass of the extended halo? If the gravitational potential of each galaxy is sufficiently flat at \( r \sim d \), for example if they are embedded in roughly NFW haloes so that the potential grows logarithmically, and if the orbit is roughly circular, then in a crude approximation the subhaloes are not affected by the mass at \( r > d \). Therefore the Virial theorem still gives a reasonable estimate of the subhalo mass, but only of the portion of the subhalo mass which lies at \( r < d \).

Note that this bound applies to pointlike and to extended objects alike, if pair of extended objects violate this bound then either they will separate or they will disassemble into a part which separates and a part which remains.

Thus in what follows it will be understood that \( M_T \) only measures the mass within a radius \( d \) of the subhalo cores.

On the other hand, if the haloes extend to \( r > d \) then the derivation of the lower bound \( M_{min} \) above is invalid. Therefore the values of \( M_{min} \) only apply to the case of haloes in which essentially all of the mass is at radii \( r < d \).

In Table 1 we report the separations and angular separations between the four pairs of satellite galaxies mentioned in the abstract as well as their relative line of sight velocity \( v_{los} \) and also the analogous quantities for the Magellanic Clouds. We rely exclusively upon the Local Group member data assembled in McConnachie (2012). When the angular separation is large the line of sight velocities are not parallel and so our method can overestimate the mass. We use equation (3) to determine the minimum mass \( M_{min} \) of each system. For comparison we include \( M_{hl} \), the known mass within the half-light radii of each system using the method of Walker et al. (2009) and Wolf et al. (2010).

Table 1. Minimum masses and tidal radii of four candidate binary systems in our Local Group and the Magellanic clouds, calculated under the assumption that these pairs are gravitationally bound. All distances are given in kpc and velocities in km s\(^{-1}\). \( M_T \) and \( M_{min} \) are given in units of \( 10^8 M_\odot \). \( M_{hl} \) in units of \( 10^9 M_\odot \) and \( M_{tidal} \) in units of \( 10^{11} M_\odot \). In the case of the Magellanic Clouds, in the row \( v_{id} \), the full 3D velocity is reported and the expected mass and tidal radius are based on this 3D velocity.

| System      | Dr&UMi Leo | Leo | MC |
|-------------|------------|-----|----|
| \( d \)     | 23\( \pm \)2 | 25\( \pm \)11\( \pm \)10 | 33\( \pm \)16\( \pm \)0 | 59\( \pm \)39\( \pm \)4 |
| ang.        | 17.4       | 2.9 | 2.5 | 1.0 |
| \( v_{los} \) | 44.1 \( \pm \)0.1 | 41.0 \( \pm \)3.4 | 30.2 \( \pm \)2.3 | 10.7 \( \pm \)1.4 |
| \( M_T \)   | 31         | 30  | 21  | 5   |
| \( M_{min} \) | 5.2\( \pm \)0.4 | 4.9\( \pm \)2.3\( \pm \)2.1 | 3.5\( \pm \)1.8\( \pm \)0.5 | 0.8 \( \pm \)0.5 |
| \( M_{hl} \) | 10.2       | 1.2 | 25  | 121 |
| \( r_{id} \) | 77         | 167 | 66.5| 164.5|
| \( M_{tidal} \) | 7.4       | 12.2 | 6.0 | 10.4 |
| \( r_{tidal} \) | 15           | 27  | 12  | 15  |
| \( M_{min} \) | 8           | 15  | 7   | 8   |
| \( M_{tidal} \) | 15           | 27  | 12  | 15  |

Table 2. Data relevant for the tangential velocity estimates of three candidate binary satellites.

| System      | Dr&UMi Leo | Leo | MC |
|-------------|------------|-----|----|
| \( r \) (kpc) | 77 \( \pm \)3  | 167 \( \pm \)6  | 57 \( \pm \)2 |
| \( r_1 - r_2 \) (kpc) | 2 \( \pm \)7  | 24 \( \pm \)12 | 13 \( \pm \)4 |
| \( (v_1^2 - v_2^2) \) (10^8 km^2/s^2) | 2.0 | 3.3 | 4.6 |

Thus in what follows it will be understood that \( M_T \) only measures the mass within a radius \( d \) of the subhalo cores.

On the other hand, if the haloes extend to \( r > d \) then the derivation of the lower bound \( M_{min} \) above is invalid. Therefore the values of \( M_{min} \) only apply to the case of haloes in which essentially all of the mass is at radii \( r < d \).

In Table 1 we report the separations and angular separations between the four pairs of satellite galaxies mentioned in the abstract as well as their relative line of sight velocity \( v_{los} \) and also the analogous quantities for the Magellanic Clouds. We rely exclusively upon the Local Group member data assembled in McConnachie (2012). When the angular separation is large the line of sight velocities are not parallel and so our method can overestimate the mass. We use equation (3) to determine the minimum mass \( M_{min} \) of each system. For comparison we include \( M_{hl} \), the known mass within the half-light radii of each system using the method of Walker et al. (2009) and Wolf et al. (2010).

Note that the condition that the systems are gravitationally bound requires that the total mass be about 3 orders of magnitude greater than the known mass \( M_{hl} \) in the region inhabited by stars and furthermore these two masses have no obvious correlation. This in itself is not an argument against the pairs being gravitationally bound, but it is a strong constraint on the allowed haloes. Indeed, many of the haloes for these galaxies suggested in the literature have appreciably lower total masses. For example, assuming an NFW halo profile with a specific relation between the mass and the concentration Walker et al. (2007) find that the Virial mass of the Draco dwarf is only \( 9 \times 10^7 M_\odot \), yielding a total mass much smaller than that in Table 1. On the other hand, some studies do suggest that the Milky Way has subhaloes with masses in excess of \( 10^{10} M_\odot \). For example, Font et al. (2011) find that about 10 per cent of Milky Way subhaloes may have masses in this range, rendering these high masses perhaps unlikely but nonetheless plausible.
Interestingly, these masses are somewhat in tension with the results of the Millennium-II simulation. Boylan-Kolchin et al. (2010) have shown that Milky Way sized galaxies in these simulations in general only have two to five subhaloes with masses greater than 10^{-3} times the mass of the host and generally none with masses in excess of 7 \times 10^{-3} times that of their host. In the case of the Milky Way and Andromeda, this translates to less than 10 haloes of mass greater than 10^8 \, M_\odot and usually none with mass greater 10^{10} \, M_\odot. Thus masses of the order of the values of \( M_f \) reported in Table 1 are exceedingly rare given the merger histories considered in these simulations.

2.1 Magellanic Clouds

For illustration we will apply a similar analysis to the Magellanic Clouds, whose gravitational association has long been suspected. Unlike the other pairs considered here, the line of sight velocities have been measured precisely. As a result, extensive modelling of the precise orbits of this system has been considered in the literature, with full N-body simulations instead of the naive point approximations used in this paper. Therefore, the estimates derived below should not be interpreted as providing new information as to the orbits of the Magellanic Clouds, but merely as an illustration of the methods used here in a familiar and well-studied setting.

The line of sight velocities (Harris & Zaritsky 2006) are respectively 262.2 km s^{-1} and 145.6 km s^{-1} for the LMC and the SMC. The angle between these lines of sight is 20.7 and so they are rather far from parallel. Therefore simply subtracting the two line of sight velocities to obtain a relative line of sight velocity is a poor approximation. The tangential velocities of both the LMC (Kallivayalil et al. 2006a) and SMC (Kallivayalil, van der Marel & Alcock 2006b) have been measured by the Hubble Space Telescope.

In the (east, north, radial) basis the best-fitting velocities of the clouds with respect to the Sun, in km s^{-1}, are

\[ v_{LMC}^{(\text{spher})} = (482, 104, 262), \quad v_{SMC}^{(\text{spher})} = (340, -341, 146). \] (5)

Let \( \theta \) and \( \phi \) be the spherical coordinate angles corresponding to the right ascension and declination, respectively

\[ (\theta, \phi)_{LMC} = (-69.8, 80.9), \quad (\theta, \phi)_{SMC} = (-72.8, 13.2). \] (6)

Then the velocities in Cartesian coordinates are easily found, in units of km s^{-1}, to be

\[ v_{LMC}^{(\text{Cart})} = (-446, 262, -210), \quad v_{SMC}^{(\text{Cart})} = (-353, 267, -240). \] (7)

The norm of the best-fitting relative velocity is

\[ |v| = \sqrt{v_{LMC}^{(\text{Cart})} - v_{SMC}^{(\text{Cart})}} = 98 \, \text{km s}^{-1}. \] (8)

As we have the absolute velocity difference and not just the line of sight velocity difference, one may determine the mass using the first equality in equation (4). We obtain

\[ M_T = 5.5 \times 10^{10} \, M_\odot, \quad M_{\text{min}} = M_T/2 = 2.7 \times 10^{10} \, M_\odot \] (9)

where as described above the minimum mass \( M_{\text{min}} \) is calculated by setting the sum of the kinetic and potential energy to zero.

3 TIDAL RADII

As noted by Blana et al. (2012) in this context, for an orbiting satellite galaxy system to be gravitationally bound it is not sufficient that the sum of the kinetic and potential energy be negative. It is also necessary that the binding be sufficiently strong so that it be disrupted by tidal forces arising from the host galaxy. This can be restated simply as the condition that the tidal radius for each galaxy be greater than the separation between the two galaxies in the pair.\(^2\)

The tidal radius of a mass \( M \) object in a circular orbit of radius \( R \) about an object of mass \( M_s \) is (King 1962)

\[ r_{\text{tidal}} = R \left( \frac{M}{3M_s} \right)^{1/3}. \] (10)

In principle, the tidal radius is further reduced as a consequence of the fact that orbits are generally elliptical and so the bound system will eventually pass closer to the massive body. As the Milky Way and Andromeda are extended objects, \( M_s \) is only the part of the host’s mass at smaller radii than the distance to the satellite. For simplicity we will use the average, \( r_{\text{aver}} \), of the distances from the two paired satellites to their host and we will make the crude approximation that the masses of the two satellites are equal. For the Milky Way mass profile we will use the best-fitting model of McMillan (2011) and for Andromeda that of Corbelli et al. (2010). More specifically, for the Milky Way (Andromeda) we will assume a pointlike baryonic mass of \( 7 \times 10^{10} \, M_\odot \) \((14 \times 10^{10} \, M_\odot)\) at the centre and dark matter distributed in an NFW profile with a concentration \( c = 15.3 \) \((12)\) and a dark plus baryonic mass of \( M_s = 1.45 \times 10^{12} \, M_\odot \) \((1.2 \times 10^{12} \, M_\odot)\) within a virial radius defined such that the average density inside is 94 \((98)\) times the critical density assuming a Hubble parameter of \( h = 0.71\).

We apply equation (10) to produce tidal radii \( r_{\text{tidal}} \) for the 10 dwarfs in the five binary systems, reporting the results in Table 1 together with the mass \( M_s \) of the host galaxy which is within the average radius \( r_{\text{aver}} \) of the satellites. More precisely, the lower bounds on the masses yield lower bounds \( r_{\text{tidal}} \) on the tidal radii while the crude estimates \( M_s \) yield estimates \( r_{\text{tidal}} \). The crudeness of the estimates \( M_s \) is somewhat alleviated by the fact that the mass appears inside of a cuberoot in equation (10). Our conclusion, as is evident from Table 1, is that in general the condition \( r_{\text{tidal}} > d \) is not satisfied. It is only satisfied in the case of Leo IV and V and even in this case \( r_{\text{tidal}} \) and \( d \) are almost equal.

For Blana et al. (2012) the fact that this condition fails simply implied that one needs to impose a stronger lower bound on the mass of the galaxies such that the attraction can overcome the tidal force. However in our study we have not only provided a lower bound for the galactic masses, but we have also provided an average value based on isotropy and the Virial theorem. Therefore our estimates of the masses will only be poor if we are either observing the pair from a special angle or at a special moment in its orbit, for example the orbit could be extremely eccentric and we are observing it just at the nearest passage. As it is the cube root of the mass which enters in the formula for the tidal radius, these approximations would need to be much worse than one would expect statistically in order for the gravitational attraction of these systems to overcome the tidal forces of their hosts. Thus it is difficult to evade the conclusion that in most of these systems the tidal radii are less than the separations and so most or all of the pairs considered here are not gravitationally bound.

How dependent are these conclusions upon the mass model of the host galaxy? After all, if the host galaxy is lighter, the tidal radius will increase and so this constraint will weaken. To test this

\(^2\) It is only the separation in the radial direction from the host galaxy which yields a tidal force, so one might try to evade this condition if the pair separation is perpendicular to this direction. Such a situation cannot last for an entire passage about the host.
dependence we use an unusually light model of the Milky Way, that of Widrow, Pym & Dubinski (2008). Note that equation (11) of that paper, which gives the mass within a given radius, does not appear to reproduce the standard formula for the NFW case $\gamma = 1$. However the densities can be directly integrated to yield a mass within 77 kpc (167 kpc) of $3.4 \times 10^{11} M_\odot (5.3 \times 10^{11} M_\odot)$, less than half the mass of the previous model. In this case the tidal radii for Draco and UMi increase to 19 kpc, still below the lower bound on their separation. The radii for Leo IV and V increase to 36 kpc, which as before allows this pair to be bound. Therefore our conclusions remain unchanged even in this rather extreme case. However in the case of the Magellanic clouds the tidal radius is increased to 34 kpc which allows the clouds to be bound. This underlines the fact that we have nothing new to add concerning the Magellanic cloud system in this note. On the other hand, for the Andromeda satellite pairs to be bound one would require a mass model of the Andromeda galaxy with at least 20 times less mass at the relevant radii than the model considered above. Such models are strongly excluded.

There is, however, one caveat that must be kept in mind. Recall that $M_T$ only estimates the mass at radii $r < d$. An extended halo may contain appreciable mass at $r > d$, with the two visible dwarf galaxies manifested as two overdensities. In this case the tidal radius is not determined by $M_T$ alone. This is in part a result of the fact that $M_T$ only approximately corresponds to the mass at $r < d$, but more crucially it reflects the fact that the matter at $r > d$ can prevent the dwarfs from escaping when their separation exceeds $d$. We will call this the extended halo solution. In the case of Leo IV and V this solution was investigated by Blana et al. (2012) who found that it requires a mass of at least $4 \times 10^{10} M_\odot$ for each galaxy corresponding to a single extended halo with a mass of about $8 \times 10^{10} M_\odot$. Needless to say, the existence and indeed genericity of such extended haloes is in strong tension with the Millennium-II simulation claims of Boylan-Kolchin et al. (2010), which imply that, for the merger histories considered, the average number of such massive subhaloes of a Milky Way sized galaxy is about 0.1. While the extended halo solution remains a logical possibility, we will not consider it further here.

4 PAIRS FROM MERGERS WITH A COMMON PROGENITOR

If these pairs are not gravitationally bound, why are they so close physically and why do they have similar radial velocities and luminosities?

4.1 Scenarios

A first guess may be that these binary systems simply were never gravitationally bound. Perhaps it is a sheer coincidence that the two members of a pair have similar positions, velocities and luminosities. For individual pairs the probability of such an occurrence has been estimated by Belokurov et al. (2008); Fattahi et al. (2013) and, considering the number of pairs, it is well below 1 per cent.

Furthermore, there is weak evidence for pairing in other systems. James & Ivory (2011) have identified nine distant galaxies with two or three satellite galaxies and one with five satellite galaxies. Of these, they found that in the case of five of these systems there exists a pair of satellites whose distance from the host greatly exceeds the projected separation of the pair. While projected distance alone certainly is insufficient to identify a binary system, nonetheless such a distribution in five of the 10 cases would be quite unlikely were the satellites distributed randomly. On the other hand, Robotham et al. (2012) found that the presence of two satellites with masses comparable to the Magellanic clouds is quite rare overall, appearing in only two systems, representing 0.4 per cent their survey. This is consistent with the product of the fraction of LMC and SMC mass galaxies found individually, suggesting that the formations of the elements of the pairs are independent. More importantly, both pairs were well separated indicating that neither is a binary system.

Belokurov (2013) has suggested that the phase space correlations in the Milky Way and Andromeda’s satellite systems could be explained if these satellites condensed from a once gravitationally bound object, or a piece of such an object, which has been accreted by the host galaxy. We will now argue that such a scenario may also be able to explain the abundance of gravitationally unbound satellite pairs; however it requires a rather restrictive accretion history which may motivate the search for alternative explanations.

Such scenarios can be divided into two categories. First it may be that both galaxies in a given pair were part of an extended structure which merged with our Local Group. This was essentially proposed by Belokurov et al. (2008) for Leo IV and V, although the proposed structure was later revealed to be a foreground (Jin et al. 2012). The second possibility is that these pairs existed as bound binaries but are now approaching their host galaxies for the first time and so are in the process of disassociating. In the case of Milky Way satellites, as data arrive concerning tangential velocities of these systems a more accurate picture of their past orbital histories will emerge and these scenarios may be evaluated.

In this section, we will see that fairly strong assumptions are necessary in both cases. The first category may require recent large mergers in both the Milky Way and the Andromeda systems or else it is difficult to see why the pairs should be separating just now. Similarly, the second may require us to live at a special moment when all of these pairs are arriving close to their host for their first time.

4.2 Comparison of energy and angular momenta

How can such scenarios be tested?

First one must determine just when the satellite galaxies in each pair formed or became unbound. If indeed they are not gravitationally bound to each other, then the estimates of their masses in Section 2 are unmotivated. The masses must still satisfy the lower bounds $M_{\text{th}}$ of the order of $10^7 M_\odot$ given the dispersions of their stars, but can well be much less than $10^{10} M_\odot$ so as to agree with the results of simulations. As a result of these low masses, at the distances of 10 kpc or more by which these pairs are separated, the gravitational attraction between the galaxies in a given pair is irrelevant.

Thus each galaxy in a pair follows an independent orbit about the host galaxy. We know that the galaxies in each pair are separated by about 30 kpc and have relative velocities of the order of $30 \text{ km s}^{-1}$. Thus, one might suspect that they separate quickly and so such pairs should not exist for long. However, it could be that, as a result for example of the compactness of their common progenitor, the two satellites in a pair have essentially the same centre of mass energy and angular momentum about their host. In this case, they would inhabit distinct orbits with the same ellipticity and perigalactic distance and so, while the distance between the satellites and the
difference between their radial velocities would change in time, this change would be periodic and so such a small difference could be stable over the cosmological time since these satellites formed.

Is it possible that the satellites in each pair indeed have the same total energy and angular momentum about their host? Consider two Milky Way satellites which are separated from the Milky Way by distances $r_1$ and $r_2$ with radial velocities $v'_1$ and $v'_2$. As we are much closer to the centre of the Milky Way than the satellites, these radial velocities with respect to the Milky Way can be well estimated by simply correcting the radial velocity with respect to the Sun by the Sun’s motion about the centre of the Galaxy. This would not be the case for satellites of Andromeda. Let $v'_1$ and $v'_2$ be the magnitudes of their tangential velocities, in other words the norm of the velocity two-vector normal to the radial direction from the centre of the Milky Way to the satellite. Now let $M$ be the mass of the Milky Way out to the distance $r_1$. Since $r_1$ and $r_2$ are close, we will make the further approximation that this is equal to the mass of the Milky Way out to $r_2$.

Now the condition that both satellites in a pair have the same angular momentum is

$$r_1v'_1 = r_2v'_2$$

(11)

whereas the condition that they have the same centre of mass kinetic plus potential energy is

$$\frac{1}{2} (v'_1)^2 + 1 \frac{1}{2} (v'_2)^2 - \frac{GM}{r_1} = \frac{1}{2} (v'_1)^2 + 1 \frac{1}{2} (v'_2)^2 - \frac{GM}{r_2}.$$  

(12)

Combining these conditions we can find the tangential velocity squared of either satellite

$$\left( v'_1 \right)^2 = 2GM \frac{r_2}{v_1(r_1 + r_2)} + \left[ \left( v'_2 \right)^2 - \left( v'_1 \right)^2 \right] \frac{r_2^2}{r_2^2 - r_1^2}.$$  

(13)

To leading order in an expansion about $r = r_1$ with respect to $(r_2 - r_1)/r_1$ this reduces to

$$\left( v'_1 \right)^2 = \frac{GM}{r} + \left[ \left( v'_2 \right)^2 - \left( v'_1 \right)^2 \right] \frac{r}{2(r_2 - r_1)}.$$  

(14)

We may recognize the first term on the right hand side as $v^2$ for a circular orbit.

4.3 Tangential velocities of Milky Way satellites

What would this imply for our Milky Way satellite pairs?

The relevant data is summarized in Table 2. Let us begin with Draco and Ursa Minor. The radial velocities are known quite well. In the case of Draco and Ursa Minor they are respectively $v_1 = -96$ km s$^{-1}$ and $v_2 = -85$ km s$^{-1}$. In particular, Draco is infalling faster than Ursa Minor. This leads us to a tangential velocity for Draco of

$$\left( v'_1 \right)^2 = 4.2 \times 10^4 \text{ (km s}^{-1}\text{)}^2 + 2 \times 10^4 \text{ (km s}^{-1}\text{)}^2 \frac{38 \text{ kpc}}{(r_2 - r_1)}.$$  

(15)

The radial distances are known somewhat less precisely $r_1 = 76 \pm 6$ kpc and $r_2 = 78 \pm 3$ kpc. Therefore it is not known which is closer.

If Ursa Minor is closer than Draco, which is marginally preferred by the data, then equation (15) gives a high tangential velocity for Draco. Indeed with 1σ of confidence $0 < r_2 - r_1 < 9$ kpc and so $(v'_1)^2$ is greater than $5 \times 10^4 \text{ (km s}^{-1}\text{)}^2$, so $v'_1 > 220$ km s$^{-1}$. On the other hand if $0 < r_1 - r_2 < 2$ kpc then $(v'_2)^2$ will be negative which is clearly impossible, so identical orbits for the two satellites imply that either $r_2 > r_1$ and $v'_1 > 220$ km s$^{-1}$ or else $r_2 < r_1 - 2$ kpc and $v'_1 < 200$ km s$^{-1}$. Within 1σ bounds on the relative radial distances, this tangential velocity is high enough to be measured by Gaia and so this possibility is falsifiable in the near future.

Next we will consider Leo IV and Leo V. In this case the relative velocities are much greater $v'_1 = 13 \pm 1$ and $v'_2 = 59 \pm 3$. Leo V is receding more quickly than Leo IV. While they lie upon almost the same line of sight, at $r_2 = 179 \pm 10$ kpc Leo V appears to be more distant than Leo IV at $r_1 = 155 \pm 6$ kpc, so the distance between these satellites is increasing. In particular, the second term in equation (15) is positive and is between $7000$ and $20000 \text{ (km s}^{-1}\text{)}^2$. Again, this leads to a large tangential velocity for the Leo’s which is easily within the sensitivity of the Gaia mission.

So far, we have been unable to present conclusions, only predictions, regarding the scenario in which the elements of each pair have a common progenitor. The problem is that the tangential velocities of these dwarf spheroidal galaxies are unknown. However, the tangential velocities of the Magellanic clouds are well known. Unfortunately, they are so massive that their gravitational interactions cannot be neglected. Indeed, there seem to be gaseous (Muller & Bekki 2007) and perhaps stellar (Nidever et al. 2013) features created by a collision between the two satellites 200 million years ago. Nonetheless, a naive application of equation (15) leads to a tangential velocity for the SMC of $110 \pm 30$ km s$^{-1}$, which is more than 3σ less than the measurement reported by Kallivayalil et al. (2006b).

Conclude that the hypothesis that the satellites in each pair follow similar orbits because they have the same total energy and angular momentum per mass leads to very non-trivial predictions for all three Milky Way pairs. In the case of the two of these pairs the predictions can easily be tested by Gaia. In the case of the Magellanic clouds this prediction is already strongly excluded by existing data. Therefore, in what follows we will not impose any such constraint on the angular momenta and energies.

4.4 Independent motions

Recall that the radial velocities of the members of each pair agree to within about 30 km s$^{-1}$ and their positions agree to within about 30 kpc. Therefore, one may attempt to estimate the differences in their orbits. Our isotropy assumptions on the relative velocities of the satellites imply 3D relative velocities of the order of 50 km s$^{-1}$. On the other hand the Virial theorem, together with their potential energies, leads to total velocities of the order of 150 km s$^{-1}$ in the reference frame of the host. Therefore, one expects a difference in kinetic energy of the order of 10 per cent. In addition, the differences in the radial distances to their hosts lead to a difference in potential energy of the order of 10–15 per cent. The conclusion of the last subsection suggests that these two differences do not cancel each other, and so we will add them as if they were independent to conclude that the total energies of two elements of a pair differ by 10–20 per cent.

As a result the semimajor axes differ by 10–20 per cent and so the orbital periods differ by of the order of 15–30 per cent. A crude estimate of this already approximate effect is obtained by stating that the separation between the elements of a pair changes by 15–30 per cent of their 150 km s$^{-1}$ orbital velocity, leading to a 20–50 km s$^{-1}$ or 20–50 kpc Gyr$^{-1}$ change in their separation.

What would such a rate of change of the separation of the satellites in each pair imply? To determine this, one needs to determine the initial separations of the satellite pairs. This can be extrapolated from the wealth of data on Local Group satellites assembled by McConnachie (2012).
Milky Way Satellites

The crucial observation is as follows. There are 26 Milky Way satellites with well-known radial velocities, leading to 325 potential pairs. Pairs which condensed recently from the same compact progenitor may be expected to have similar line of sight velocities, so we will restrict our attention to pairs with line of sight velocities that agree within 90 km s$^{-1}$. As plotted in Figs 1 and 2, this leaves 95 pairs, although it excludes the Magellanic clouds whose progenitor may have been large. Now if the distance $d$ between the two satellites in the pair is greater than half of the distance $r_{av}$ from the centre of the pair to the Milky Way, then their proximity is well explained by their mutual attraction to the Milky Way and so there is no need to invoke an unobserved common ancestor. But if we further restrict our attention to satellite pairs satisfying $d < r_{av}/2$ then we find only two pairs, Draco and Ursa Minor and also Leo IV and V, as is shown in Fig. 3. These are separated by just 23 and 25 kpc, although our conditions allowed for separations as large as 90 kpc. The total volume within a separation of 90 kpc is 60 times larger than that with a separation of 25 kpc, and so a random distribution of pairs would have led to much larger separations.

There is a natural explanation for the small separations within the common progenitor scenario. If the size of the common progenitors is of the order of 30 kpc or less, then one may expect the pairs which condensed from that progenitor to be separated by less than 30 kpc.

Thus, an analysis of the Milky Way satellite pairs seems to suggest that, in the common progenitor scheme, the sizes of the progenitors is at most about 30 kpc. Now we can return to the crude estimate that the separations are changing by 20–50 kpc Gyr$^{-1}$. If indeed the initial separations were less than 30 kpc and the separations today are less than 30 kpc, then this gives an upper limit on the time that has elapsed since these satellites condensed of roughly 2 Gyr. As the pairs are very much separated spatially, each seems to have condensed from a different progenitor. Thus, the common progenitor model is fairly constrained, both common progenitors in the Milky Way condensed into satellite galaxies in the past 2 Gyr.

The absence of pairs with 30 kpc $< d < r_{av}/2$ has a further implication. Not only are the pairs which are observed quite young, but there seems to be an absence of older pairs. If the condensation of progenitors into satellites pairs were common, one would expect pairs of all ages and so of all separations, in conflict with observations. If on the other hand it were rare, then why would so many events have happened in the past 2 Gyr?

Andromeda Satellites

These are all rather strong statements to extract from rather small samples of pairs. However a similar analysis can, in principle, be applied to the Andromeda system. One major disadvantage in the case of Andromeda satellites is the comparatively poor knowledge of the distances between the satellites and their host. Nonetheless, the precise knowledge of the angular positions of the satellites yields robust lower bounds on their separations, which in most cases is already sufficient to conclude that the separation, $d$, between two satellites exceeds half of the distance, $r_{av}$, to Andromeda.

21 Andromeda satellites have well-measured radial velocities, leading to 210 potential pairs. We will restrict our attention to pairs for which the radial velocities with respect to the Sun agree within 90 km s$^{-1}$. This leaves 75 pairs with separations shown in Fig. 4. Now a minimum distance between the pairs can be estimated by fixing the radial distances between each Andromeda satellite and the Sun to be equal, for simplicity we will set them to be equal to the distance to the Andromeda galaxy. This allows us to further restrict our attention to those pairs separated by a maximum distance $d_{min} < r_{av}/2$. As can be seen in Fig. 5, there are 10 such pairs, including the two pairs discussed in this note. The characteristics of these pairs are summarized in Table 3.

Of the eight potential new pairs, only one pair, consisting of Andromeda XI and Andromeda XIV, has a best-fitting
Table 3. Andromeda pairs with radial velocities that agree to within 90 km s\(^{-1}\) and minimum distances that are less than half of \(r_{\text{av}}\), the average distance to Andromeda. Distances and velocities are reported in kpc and km s\(^{-1}\), respectively.

| Pair             | \(d_{\text{min}}\) | \(d_{\text{av}}\) | \(r_{\text{av}}\) | \(|v_1^\circ - v_2^\circ|\) |
|------------------|---------------------|-------------------|-------------------|-----------------------------|
| And I&III        | 33                  | 33\(^{+12}_{-0}\) | 66                | 30 \pm 2                    |
| NGC 147&185     | 13                  | 59\(^{+39}_{-36}\) | 164               | 11 \pm 1                    |
| And XI&XIV       | 56                  | 60\(^{+150}_{-2}\) | 133               | 61 \pm 5                    |
| And XII&XIV      | 62                  | 151\(^{+170}_{-39}\) | 147              | 77 \pm 4                    |
| And II&XII       | 68                  | 269\(^{+45}_{-154}\) | 182              | 1 \pm 8                     |
| And II&Triangulum| 61                  | 168 \pm 28        | 195              | 14 \pm 2                    |
| And XVI&I        | 76                  | 229 \pm 53        | 168              | 9 \pm 5                     |
| And XVI&III      | 79                  | 233 \pm 53        | 177              | 39 \pm 5                    |
| And XVI&XI       | 37                  | 236\(^{+65}_{-75}\) | 191              | 35 \pm 7                    |
| And XVI&XV       | 78                  | 122\(^{+38}_{-38}\) | 226              | 46 \pm 9                    |

In excess of 50 km s\(^{-1}\) or else the best-fitting radial distances lead to large separations. Thus, the distribution of Andromeda pairs is consistent with a low average separation, of the order of 30 kpc, and no satellites in the 30–90 kpc separation range. On the other hand, given a homogeneous distribution of satellite distributions in phase space one may have expected pairs with minimum distances in the 40–90 kpc range and relative velocities beneath 50 km s\(^{-1}\), but such pairs appear to be missing.

Thus, like pairs of Milky Way satellites, the pairs of Andromeda satellites considered in this note also appear to have condensed less than 3 Gyr ago and there is mild evidence that older pairs are not present. This is interesting because, in the case of many of these pairs, although certainly not the Magellanic clouds, star formation would have ceased before the pairs condensed. This suggests that both the metallicities and stellar populations of the two satellites in a pair should be similar. For now this is difficult to test in the case of Leo IV and V because of the foreground contamination in Leo V. However, tangential velocity measurements by the Gaia satellite will help to separate Leo V from the foreground. On the other hand Ursa Minor is appreciably more metal poor than Draco (Kirby et al. 2011), albeit with a difference which is smaller than the metallicity spread.

The simplest explanation for the lack of older systems is that, due to dynamical friction, they have already coalesced with their hosts. However, if their masses \(M_f\) indeed are less than \(10^{11}\) M\(_\odot\) then the \(N\)-body simulations of Boylan-Kolchin, Ma & Quataert (2008) suggest that, even if their orbits are quite eccentric, 2 to 3 billion years is insufficient for this process.

The likelihood that all of these mergers occurred sufficiently recently is difficult to estimate; however it motivates our search for other potential explanations for the proximities of these gravitationally unbound pairs.

5 FUTURE DIRECTIONS

Should the common progenitor explanation for the abundance of close pairs of satellites with similar radial velocities be falsified by future data, then what? One might try to explain the attraction of the satellites in a pair by modifying gravity; however given the orders of magnitude separating \(M_f\) and \(M_{\text{halo}}\), the modification would have to be so extreme that it would already be excluded by precision gravity tests. Another possibility is that the dark matter haloes might both be very massive, with masses of the order of \(M_f\), and also interact.
non-gravitationally. If the halo mass is of the order of \( M_{\odot} \), then the non-gravitational interaction need not be much stronger than the gravitational interaction, and so in principle tension with precision gravity tests may be reduced. In a relativistic field theory, such long range non-gravitational interactions imply that dark matter couples to a particle, besides the graviton, which is lighter than \( 10^{-25} \) eV. Such interactions have often been invoked to remedy weaknesses of weakly interacting massive particle (WIMP) models. Examples involving light scalar fields include, for example, that of Matos & Guzman (2000). Recently, Slepian & Goodman (2011) have claimed that scalar field models which are capable of reproducing flat rotation curves generically run afoul of the upper bound on the cross-sections implied by observations of the Bullet cluster (Randall et al. 2008). However this pathology can in turn be cured by the addition of a dark gauge symmetry in models in which dark matter haloes are giant \( 't \) Hooft-Polyakov magnetic monopoles (Evslin & Gudnason 2012).

Models with long-range non-gravitational interactions share one common feature. Stable dark matter haloes in such models may extend beyond their tidal radii; in fact in many models they must. CDM WIMPs at astrophysical distances can only be bound gravitationally and so can never form stable structures that extend beyond their tidal radii. Therefore an observation that stable dark matter haloes extend beyond their tidal radii would simultaneously falsify all models of dark matter in which the only long distance interaction is gravity, including WIMPs. The current study certainly does not falsify any models; the common progenitor explanation for the coincidental positions of these pairs is quite plausible and consistent with WIMP phenomenology. However, in the future the outer regions of dwarf spheroidal haloes will be mapped both using lensing and also via tangential velocity measurements of stellar tracers at large radii while their total masses may be determined via measurements of velocity changes of stars in the Milky Way’s disc (Feldmann & Spolyar 2013) and so such an exclusion will be feasible.

On the 2013 December 19, the European Space Agency launched the Gaia space telescope. Due to its proximity, at 76 kpc, we suggest that the proposed binary system consisting of the Draco and Ursa Minor dwarfs would be fruitful to observe for three reasons. First of all, the average of the transverse stellar motions will give a reasonably accurate measurement of the transverse velocities of the two galaxies and so allow a more precise determination of their orbits and thus also their masses. Secondly, by determining the transverse velocities of the stars, the degeneracy which plagues the Jeans equation (Binney & Mamon 1982) can be broken, allowing the dispersive motion of the stars to reveal the underlying mass profile. As these galaxies, unlike the Magellanic clouds, are everywhere dark matter dominated, this will provide a direct measurement of the dark matter halo’s shape. Finally, the transverse velocities can be used to distinguish members of the galaxies from the background. If, as some dark matter models suggest, the dark matter haloes of these galaxies extend far beyond the furthest yet identified stars, a wealth of members await discovery in the regions where they are outnumbered by non-members. These extra members can be used to trace out, for the first time, the outer regions of a dwarf spheroidal galaxy’s dark matter halo.

ACKNOWLEDGEMENTS

I would like to thank Malcolm Fairbairn and Sven Bjørke Gudnason for discussions and comments on this draft. JE is supported by the Chinese Academy of Sciences Fellowship for Young International Scientists grant number 2010Y2J101, NSFC grant 11375201 and a KEK Fellowship.

REFERENCES

Bellazzini M., Oosterloo T., Fraternali F., Beccari G., 2013, A&A, 559, L11
Belokurov V., 2013, New Astron. Rev., 57, 100
Belokurov V. et al., 2008, ApJ, 686, L83
Binney J., Mamon G. A., 1982, MNRAS, 200, 361
Blana M., Fellhauer M., Smith R., 2012, A&A 542, A61
Boylan-Kolchin M., Ma C.-P., Quataert E., 2008, MNRAS, 383, 93
Boylan-Kolchin M., Springel V., White S. D. M., Jenkins A., 2010, MNRAS, 406, 896
Corbelli E., Lorentzoni S., Walterbos R., Braun R., Thilker D., 2010, A&A 511, A89
David D. S., Bird C. M., Mushotzky R. F., Odehwaht S. C., 1995, ApJ, 440, 48.
de Jong J. T. A., Martin N. F., Rix H.-W., Smith K. W., Jin S., Macciò A. V., 2010, ApJ, 710, 1664
Evslin J., Gudnason S. B., 2012, preprint (arXiv:1205.0260)
Fattahi A., Navarro J. F., Starkenburg E., Barber C. R., McConnachie A. W., 2013, MNRAS, 431, L73
Feldmann R., Spolyar D., 2013, MNRAS, preprint (arXiv:1310.2243)
Font A. S. et al., 2011, MNRAS, 417, 1260
Harris J., Zaritsky D., 2006, AJ, 131, 2514
Ibata R. A. et al., 2013, Nature, 493, 62
James P. A., Ivory C. F., 2011 MNRAS, 411 495
Jebsen J. T., 1921, Arkiv för Matematik, Astronomi och Fysik 15, 1
Jin S., Martin N., de Jong J., Conn B., Rix H.-W., Irwin M., 2012, ASP Conf. Ser. Vol. 458. On the Nature of the Stellar Bridge Between Leo IV and Leo V. Astron. Soc. Pac., San Francisco, p. 153
Kallivayalil N., van der Marel R. P., Alcock C., Axelrod T., Cook K. H., Drake A. J., Geha M., 2006a, ApJ, 638, 772
Kallivayalil N., van der Marel R. P., Alcock C., 2006b, ApJ, 652, 1213
Kingsley, I., 1962, AJ, 67, 471
Kirby E. N., Lanfranchi G. A., Simon J. D., Cohen J. G., Guhathakurta P., 2011, ApJ, 727, 78 [Erratum; 750, 173 (2012)]
Kroupa P., Theis C., Boly C. M., 2005, A&A, 431, 517
Matos T., Guzman F. S., 2000, Classical Quantum Gravity, 17, L9
McConnachie A. W., 2012, AJ, 144, 4
McMillan P. J., 2011, MNRAS, 414, 2446
Muller E., Bekki K., 2007, MNRAS, 381, L11
Nievergelt D. L., Monachesi A., Bell E. F., Majewski S. R., Munoz R. R., Beaton R. L., 2013, ApJ, 779, 145
Pawlowski M. S., Kroupa P., 2013, MNRAS, 435, 2116
Pawlowski M. S., Kroupa P., Jerjen H., 2013, MNRAS, 435, 1928
Randall S. W., Markevitch M., Clowe D., Gonzalez A. H., Bradac M., 2008, ApJ, 679, 1173
Robotham A. S. G. et al., 2012, MNRAS, 422, 1448
Slepian Z., Goodman J., 2011, MNRAS, 427, 839
Tonnesen S., Cen R., 2012, MNRAS, 425, 2313
van den Bergh S., 1998, AJ, 116, 1688
Walker M. G., Mateo M., Olszewski E. W., Gneden O. Y., Wang X., Sen B., Woodroofe M., 2007, ApJ, 667, L53.
Walker M. G., Mateo M., Olszewski E. W., Peñarrubia J., Evans N. W., Gilmore G., 2009, ApJ, 704, 1274 [Erratum; 710, 886 (2010)]
Widrow L. M., Pym B., Dubinski J., 2008, ApJ, 679, 1239
Wolf J., Martinez G. D., Bullock J. S., Kaplinghat M., Geha M., Munoz R. R., Simon J. D., Avedo F. F., 2010, MNRAS, 406, 1220