DID THE MILKY WAY DWARF SATELLITES ENTER THE HALO AS A GROUP?

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ABSTRACT

The dwarf satellite galaxies in the Local Group are generally considered to be hosted in dark matter subhalos that survived the disruptive processes during infall onto their host halos. It has recently been argued that if the majority of satellites entered the Milky Way (MW) halo in a group rather than individually, this could explain the spatial and dynamical peculiarities of its satellite distribution. Such groups were identified as dwarf galaxy associations that are found in the nearby universe. In this paper, we address the question whether galaxies in such associations can be the progenitors of the MW satellite galaxies. We find that the dwarf associations are much more extended than would be required to explain the disklike distribution of the MW and Andromeda satellite galaxies. We further identify a possible minor filamentary structure, perpendicular to the supergalactic plane, in which the dwarf associations are located, that might be related to the direction of infall of a progenitor galaxy of the MW satellites, if they are of tidal origin.

Key words: galaxies: dwarf – galaxies: evolution – Galaxy: halo – Local Group

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1. INTRODUCTION

Dwarf galaxies in the Local Group, and satellite galaxies of the Milky Way (MW) and Andromeda (M31) in particular, are of great importance to understand the physics of structure formation on galaxy scales because they can be studied in unsurpassable detail. Commonly, they are associated with cosmological substructures that entered the MW halo and it has been inferred, assuming that the dwarf galaxies are in virial equilibrium, that they are dominated by a massive dark matter component though the nature of this component is still disputed (Gilmore et al. 2007). There are, however, some puzzling findings not yet completely explained.

For instance, it had been noticed that the number of observed satellite galaxies in the Local Group is at least an order of magnitude smaller than expected from cold dark matter (CDM) simulations (Moore et al. 1999; Klypin et al. 1999; Diemand et al. 2008). Different scenarios were subsequently proposed to explain the satellite galaxies in the Local Group in the context of being CDM-dominated subhalos: Stoehr et al. (2002) argued that only the most massive subhalos were able to form stars and the rest thus remains dark. Libeskind et al. (2005) proposed that current satellite galaxies are those with the most massive progenitors, also found by Strigari et al. (2007) who alternatively found accordance with the earliest forming halos. In contrast, Sales et al. (2007b) argued for low-mass systems being the origin of satellite galaxies, or it has been suggested that observers just overlooked all the hundreds of satellite galaxies surrounding the MW due to their extreme low star densities (Tollerud et al. 2008).

Recently, the interesting scenario was put forward that the satellite galaxies did not enter the MW halo individually in a random fashion, but rather in groups. Li & Helmi (2008) argued that if only one or two groups fell into the MW halo, this could account for the observed highly anisotropic spatial appearance of MW companions, the disk of satellites (DoS; Metz et al. 2007). D’Onghia & Lake (2008) suggested that groups formed within LMC-like dark matter host halos and that these hosts are able to produce many more satellites in subhalos than in an MW-like host halo. They predicted that such groups are visible today and linked them as the dwarf associations found by Tully et al. (2006).

Here, we study the properties of the dwarf associations and compare them to the satellite galaxies of the MW. In Section 2.1, we discuss the membership of satellites in the proposed Magellanic Group. The implications of the extent of observed dwarf associations is addressed in Section 2.2 and their spatial locations are analyzed in Section 2.3. We finally discuss the proposed scenario in Section 3 and summarize our conclusions in Section 4.

2. ASSOCIATIONS OF DWARF GALAXIES

2.1. A Magellanic Group?

D’Onghia & Lake (2008) proposed that the majority of the brighter satellite galaxies of the MW originate from a single group of dwarf galaxies in dark matter subhalos with their main component being the LMC that fell late into the MW halo. Indeed, such associations of dwarf galaxies exist within 8 Mpc of the Local Group (Tully et al. 2006).

Specifically, D’Onghia & Lake proposed that the Magellanic Clouds together with the Sagittarius, Ursa Minor, Draco, Sextans, and Leo II dwarf galaxies once belonged to such a group (hereafter DL08 sample). This appears to be a rather ad hoc selected sample and is based on a mixture of different and disagreeing references. Earlier proposed streams of MW satellite galaxies that are referred to, consist of different objects (LMC, SMC, Dra, UMi, and ScL; Lynden-Bell 1976), and a second different plane as proposed by Kunkel & Demers (LMC, SMC, Dra, UMi, Car, Leo I and II; Kunkel & Demers 1976; Kunkel 1979) is ∼40° off the one proposed by Lynden-Bell. Later, Lynden-Bell associated Fornax, Leo I, Leo II, and Sculptor to the so-called FLS stream, whereas he confided Carina to the LMC group (Lynden-Bell 1982a, 1982b). It is important to note that two of the galaxies in the DL08 sample, Sextans and Sagittarius, were not known until the 1990s (Irwin et al. 1990; Ibata...
et al. 1994), and thereafter Kroupa et al. (2005) and Metz et al. (2007) did not identify an individual stream, but rather highlighted the fact that all satellite galaxies of the MW belong to a virtual plane—the DoS.

In particular, one finds that the Sagittarius dwarf galaxy today must be on a quite different orbit than the other galaxies in the proposed ensemble. Based on its location and proper-motion measurements, one arrives at an orbit that is perpendicular to that of the Magellanic Clouds (Palma et al. 2002; Metz et al. 2008). Furthermore, models describing the Sagittarius Stream suggest rather short orbital timescales for Sagittarius, $t_{\text{orb}} < 1$ Gyr, small Galactic apocentric distances, $\sim 60$ kpc, and that the dwarf must have been on this close path for several orbits (Ibata et al. 1997; Law et al. 2005; Fellhauer et al. 2006). This can only be explained in the above scenario by an early scattering event with the LMC that brought Sagittarius into a close orbit (Zhao 1998; Sales et al. 2007a). However, this is inconsistent with the recent measurements of the proper motions of the LMC/SMC system (Kallivayalil et al. 2006a, 2006b; Piatek et al. 2008).

These data suggest that the Magellanic Clouds are on their first passage about the MW or are on a very wide orbit (Besla et al. 2007; Wu et al. 2008). Consequently, the LMC is on a rather different orbit from that of Sgr.

Proper-motion data are currently available for another seven MW companion galaxies, including Fornax and Carina (Piatek et al. 2003, 2007; Dinescu et al. 2004). Combining the data, Metz et al. (2008) find that these two are compatible with the hypothesis that they are in a similar orbital plane as the LMC/SMC, but both are missing in the DLO8 sample. In summary, the selection of members of the LMC group as proposed by D’Onghia & Lake is not supported by the available data. This, however, does not invalidate the suggestion that the DoS is a result of group infall.

2.2. The Extent of Dwarf Associations

When an association of dwarf galaxies falls into a large host halo, the group gets stretched and wound up on its orbit in the halo about the host galaxy (Li & Helmi 2008). The extent of the preinfall association is characterized by $R_1^3 = (\sum_{i=1}^{N} r_i^2 / N)^{1/2}$, which is the three-dimensional inertial radius of the association as given in Tully et al. (2006). Here, $r_i$ is the distance of a galaxy from the geometrical center of a group and $N$ is the number of member galaxies in the group. After the breakup, a one-dimensional characteristic scale, the thickness of the remaining distribution of dwarf galaxies—if interpreted as a flattened structure—can be derived. It is expected that such a breakup leads to a flattened structure with mean height $R_1^1 = R_1^3 / \sqrt{3}$. Using the observed values for the nearby associations 14+12, 14+13 (excluding IC 5152), 14+07, 14+08, 17+06, 14+14, 14+19, and Dregs as given by Tully et al. (2006), we find values ranging from $R_1^1 = 150$ kpc to 210 kpc, and even up to 390 kpc if we include the loose group of the “Dregs.” These are plotted in Figure 1 against the integrated $B$-band luminosity of the groups. The solid horizontal line indicates the mean ($R_1^1 = 181$ kpc (excluding the Dregs)) with a standard deviation of 22 kpc shown by the dashed lines. Compared to the height $\Delta = 18.5$ kpc (Metz et al. 2007) of the disk of the classical satellites of the MW, shown by the diamond symbol in Figure 1, all these values are an order of magnitude (at least 4.5$\sigma$) larger than those found for the MW. Also the height of the DoS of Andromeda, $\Delta = 46$ kpc, is significantly smaller than what is found for the dwarf associations. To test the robustness of our result, we also recalculated the one-dimensional characteristic scale for all the associations, by excluding their most distant group member. In that case, the smallest value derived is $R_1^1 = 92$ kpc, and the mean is ($R_1^1 = 129 \pm 23$ kpc, which is significantly larger than the height of the DoS. If we assume that the smaller rms values are purely caused by the statistical effect of a larger sample size of the classical DoS, this can also not account for the difference: in this case, we would expect at most a height of the order 25 kpc for the MW, still $\sim 4\sigma$ smaller than for the associations. If the DoS were to originate from the late infall of an association of dwarf galaxies similar to those observed near the Local Group today, it is incomprehensible how such a distribution tightens that much to become a structure similar to the DoS.

The size of the observed associations of dwarf galaxies has another very important consequence if one assumes that they are the prototypes of an LMC group aged in isolation as proposed by D’Onghia & Lake (2008). Their suggested model is based on the idea that gas is blown out of a subhalo (by whatever process) and thermalizes to the virial temperature of the host halo. So this model implicitly assumes that a small halo—that will eventually become a dwarf satellite galaxy—is embedded in a larger host halo. Because the virial temperature of an LMC-like host halo is lower than for an MW like galaxy, they argued that the cooling of the gas is more efficient in the smaller host halo and the gas settles back into the embedded subhalos. Taking their assumed values, we find that the mass ratio of the host halos is of order $M_{\text{LMC}} / M_{\text{MW}} = 1 / 10$. This mass ratio is related to the ratio of the virial radii of the host halos by $R_{\text{vir,LMC}} / R_{\text{vir,MW}} = \sqrt{M_{\text{LMC}} / M_{\text{MW}}}$ (see, for example, Salucci & Burkert 2000; Bullock et al. 2001) which gives $R_{\text{vir,LMC}} \sim 115$ kpc for $R_{\text{vir,MW}} \sim 250$ kpc. If we now interpret $R_1^3$ as a characteristic size scale for the mutual distance between any two galaxies in a dwarf association, we see that ($R_1^3$ = 314 kpc for the dwarf galaxy associations is almost a factor 3 larger than the assumed virial radius of the LMC. Thus, it is immediately clear that dwarf galaxies are not deeply
embedded in the host halo of the main component of the groups
(see also Tully et al. 2006) and do not meet the assumptions
made by D’Onghia & Lake.

It follows that today’s dwarf galaxy associations cannot be
the evolved prototypes of a dwarf galaxy group that fell into
the MW halo, but that such a hypothetical configuration must then
have been much more compact and does not correspond to any
known existing structures.

### 2.3. Locations of Dwarf Associations

One interesting property of the MW satellite galaxies still
remains to be examined in the context of the group infall scenario
which has not been discussed in detail before: the orientation of
the prolate halo in galaxy clusters is governed by the direction
of the accretion along filamentary structures. Downscaling this
behavior to an MW-like galaxy, one expects that the spatial
distribution of the satellite galaxies is correlated with the
medium-scale filamentary structure (Knebe et al. 2004; Bailin &
Steinmetz 2005; Libeskind et al. 2007; Li & Helmi 2008). It
has, however, been shown (Metz et al. 2007) that the DoS of
the MW is highly inclined with respect to the supergalactic plane
(SGP, de Vaucouleurs et al. 1991) with an inclination angle of
~69°, i.e., almost perpendicular with respect to the medium-
scale matter distribution, as is also indicated in Figure 2 by
the thick line. If (1) structures were accreted along this main
medium-scale matter distribution and (2) these structures build
up the DoS this would not explain the orientation of the DoS.

In Figure 2, we show the projected locations of the asso-
ciations of dwarf galaxies as identified by Tully et al. (2006,
compare to their Figure 13) in the supergalactic coordinate sys-
tem. For reference, we give here the orientation of the nor-
mal of the DoS of the MW in supergalactic coordinates: (SGL,
SGB) = (348°, 8°). Five out of the nine dwarf galaxy asso-
ciations are found in projection close to the SGP, |SGB| < 30°,
and thus are likely belonging to this structure. Three out of these
associations, 14+13, 14+07, and 14+08 are, in projection, close
to the DoS too. Interestingly, three out of the four remaining
associations, 14+12, 14+14, and 14–14, are also located very
close to the line that indicates the orientation of the DoS. These
associations are found at distances of 1.4, 5.8, and 4.4 Mpc from
the Sun, respectively, but they seem not to belong to the SGP.

For a better visualization of the real spatial distribution, we
plot the locations of the dwarf associations in Figure 3 in super-
galactic Cartesian coordinates. In the left panel, supergalactic
coordinates SGY and SGZ are shown. In the right panel, the
distribution is rotated about the SGZ axis such that the DoS of
the MW, indicated by the dotted line, is seen edge-on. It is evi-
dent from that plot that 14+12 and 14+14, marked by the filled
triangles and open diamond symbols, indeed lie on the virtual
extension of the DoS of the MW. We emphasize that the DoS
is derived by finding the solution that minimizes the orthogonal
distances to that plane of the MW satellite galaxies within only
~250 kpc, while the two associations are located at distances of
1400 and 5800 kpc.

Moreover, the locations of nearby galaxies within about
10 Mpc radius as listed in Karachentsev et al. (2004) are marked
in Figure 3 by dots, smaller ones marking those galaxies at
distances >8 Mpc. The extent of nearby galaxies in the SG
plane of ~2 Mpc is clearly visible in this plot. The 14+12 group
is found at the periphery of the SG plane. While hardly any
galaxies are detected toward the supergalactic north-pole region
in the Local Void (LV; Tully & Fisher 1987), there is a crowding
of galaxies in the opposite direction with no apparent structure.
In the edge-on projection (right panel), the virtual extension of
the DoS again is close to some prominent groups: one is the
Leo I group, but it is located at a distance of 10.5 Mpc.
Another one is the M101 group at the edge of the LV. Offset
from the plane, but also at the border of the LV, is the NGC 6949
group.

The surprising finding that the dwarf associations, which are
out of the SGP, are found close to the extension of the virtual
plane of the MW DoS might have different explanations: the
simplest one being that it is just a chance finding. As Tully
et al. (2006) noted, large parts of the sky, those with galactic
latitude |b| < 30°, i.e., about half of the total sky, have not
been included in their search for dwarf galaxy associations.
Two of the dwarf associations away from the SGP are found close
to the DoS, but if another dozen associations are still awaiting
discovery they could be way off the extended virtual plane of
the MW DoS. A second possible explanation is that the locations
of the groups reflect a minor medium-scale structure, a less
pronounced filament. If this were the case, it would mean that
groups can also fall into the MW host halo along this secondary
preferred structure, which is compatible with the scenario as proposed by D’Onghia & Lake (2008).

3. DISCUSSION

D’Onghia & Lake (2008) did not characterize the properties of the group before infall studied in their simulation in a way that can be directly compared to the observed dwarf associations identified by Tully et al. (2006). Here, we showed that a prerequisite for the proposed scenario is that the subhalos are deeply embedded in the host halo of the parent galaxy. Such groups, if they would evolve in isolation, do not resemble the dwarf galaxy associations we see today as has been conjectured by D’Onghia & Lake, because they would be much too compact in comparison to the observed associations.

In contrast, such systems are likely similar to the groups as studied by Li & Helmi (2008). Here, groups were identified using a relative distance cutoff, \( d < 40 \text{ kpc} \), between pairs of subhalos at the time of accretion. So, these groups were already compact before the time of accretion, much more compact than today’s dwarf galaxy associations. There is, however, an unanswered problem with the Li & Helmi scenario, too: these authors studied one MW-like halo in a CDM simulation. In that simulation they found that about one-third of the subhalos in total fell into the halo in groups. If a DoS originates from the infall of order one group hosting luminous dwarf galaxies, this means that the majority of the groups have to remain dark, as well as most subhalos that individually entered the MW halo which are two-thirds of all subhalos in total. It is not evident which process should separate the two categories of subhalo groups, luminous and dark ones. If, in contrast, all of the groups host luminous dwarf galaxies the DoS cannot be explained since the groups can come from any direction. Alternatively, to explain the DoS in this scenario, most groups have to be very efficiently destroyed after they entered the host halo and only a few remain intact.

Additionally, the process of gas accretion into subhalos embedded in LMC-type halos is not so obvious. Due to efficient cooling at the virial temperature of LMC-type halos, D’Onghia & Lake (2008) suggest that ram pressure stripping might be less efficient for embedded subhalos. They argue that these subhalos might keep more pristine gas and that they might even accrete cold (or cooled) gas, by this becoming luminous. However, details strongly depend on the inherent physical processes. In contrast, Mayer et al. (2007) found an early gas stripping in their simulations of dwarf satellite systems. Gas might, for example, be blown out by supernova activity in shallow subhalo potentials. Furthermore, the accretion of cold gas (e.g., clumps or filaments) is only feasible if the relative velocity falls below the virial velocity. A substantial ingredient to decide on the validity of the contrasting models could be provided by studies of particular element abundances. It has also been attempted to understand the formation of the galactic stellar halo by the accretion of dSphs but until now with controversial issues. Thus, the exact interplay of heating, cooling, gas dynamics, accretion, and star formation in a complex dark matter environment still has to be investigated in detail by means of numerical models.

It might be argued that compact groups of dwarf galaxies, if they existed at early times, are not observed today because if they had evolved in isolation over a Hubble time, all its members have already merged and thus we do not observe a group but only a remnant galaxy. The merger product observable today is likely a small early-type galaxy (Naab & Burkert 2003). Only dSphs found in isolation can potentially be directly linked with evolved compact groups of dwarf galaxies, because ellipticals found in a denser region cannot be distinguished from ellipticals formed in a different manner. We scanned for nearby isolated dwarf ellipticals in the catalog of Karachentsev et al. (2004), and defined isolated dwarf ellipticals to have no other galaxy within a radius of 200 kpc and to be fainter in the B band than the brightest dwarf galaxy associations, i.e., fainter than \( M_B = -19 \), because we assumed that after merging the potential remnant evolves passively, thus becoming fainter in the blue. Only one such elliptical could be identified in the catalog, NGC 855 at a distance of 9.7 Mpc, having no other galaxy listed in the catalog within a radius of 1.1 Mpc. Walsh et al. (1990) found extended H i emission in that dwarf elliptical and Li et al. (2007) suggested that it might have undergone a recent minor merger event. This would be consistent with the hypothesis that it is the merger remnant of a compact group of dwarfs. The problem with this particular candidate is that it is at the very periphery of the volume covered by the catalog and in a region likely not completely sampled. Thus, it is unclear whether NGC 855 is really that isolated. Such objects are, however, in any
case, very rare, such that the compact-group infall scenario of Li & Helmi (2008) is unlikely able to explain that both, the MW and M31, have DoSs with comparable thickness.

There is a possibility that the central galaxy of the dwarf associations is surrounded by an additional number of dwarf spheroidals that have a too low luminosity to be included in the sample. The faintest galaxy in the associations identified by Tully et al. (2006) has an absolute magnitude of $M_B = -9.3$ (excluding the Dregs association). About half of the nine classical MW dSphs are fainter than this value (Leo II has approximately the same absolute magnitude, $M_B = -9.2$). If we adopt an apparent magnitude limit of $B = 17.5$ mag for the detection of dwarfs (Karachentsev et al. 2004), we find that two out of nine MW dSphs would be detected from a distance of 6 Mpc. Six associations have distances <6 Mpc and four out of these are at distances $\lesssim 3$ Mpc. It appears likely that if an additional population of dwarfs exists that has a luminosity function similar to the one of the MW dSphs, at least in one of the associations one such dwarf would already have been found, even if they were surrounded by four or five such dwarfs only—but to our knowledge no such companion has been found. This argument does, of course, not disprove the existence of a population of fainter satellites surrounding the main component (or all the dwarf galaxies) of the associations, but if it exists it appears likely that they must all be significantly fainter than $M_B = -9.3$, possibly more similar to the objects identified in the SDSS in recent years (Metz et al. 2009)—a scenario that can be tested observationally.

4. CONCLUSIONS

We argue that there are two main issues of the proposed group infall model: first, no groups of dwarf galaxies are observed in the vicinity of the Local Group today that are consistent with the prediction by D'Onghia & Lake (2008), i.e., which are compact enough to produce a DoS. One would need to postulate that such compact groups were common about 10 Gyr ago, and have disappeared by now. In this case, there ought to be merger remnants of such groups of dwarfs. There are no good candidates for merger remnant objects, except possibly the dwarf elliptical NGC 855 which needs further investigation to confirm its properties and possible isolated status. Furthermore, it needs to be studied what properties groups of dwarf galaxies have if they evolve in isolation, whether they merge and how intermediate structures, groups that have not yet fully merged, look like. In any case, putative compact groups appear to have been very rare making the group infall scenario as an explanation for the disks of satellites of the MW and M31 very unlikely.

The second problem is that the group infall scenario requires that not only most of the subhalos are dark, but also that most of the groups are dark. Otherwise, the DoS cannot be explained in that model, because this is only reproduced if on the order of one group fell into each, the MW and M31 halos.

An alternative scenario for the origin of the dwarf spheroidal satellite galaxies of the MW goes back to an observation already made by Zwicky in the 1950s. He pointed out that galaxies may form antihierarchically in the material thrown out off interacting large halos. These nowadays called tidal dwarf galaxies (TDGs; Mirabel et al. 1992) are well known to form in the universe (e.g., Weilbacher et al. 2003; Walter et al. 2006). Based on the identification of streams of satellite galaxies and globular clusters on the sky, in a pioneering work Lynden-Bell (1983) had suggested that the dwarf spheroidals originate from the breakup of a former larger galaxy. With the growing success of the dark matter theory this idea was, however, often overlooked and dwarf galaxies were naturally identified with accreted cosmological substructures. Kroupa et al. (2005) highlighted the issue again deeming the great plane of the MW satellites to be inconsistent with the CDM theory. Indeed, there is a strong correlation of the orbital poles of the satellites (Palma et al. 2002; Metz et al. 2008) suggesting a common origin. If the satellites were of tidal origin, this would naturally account for the orbital correlation. A tidal origin is also consistent with the possible existence of a minor filamentary structure as shown in Section 2.3. If the progenitor of the satellite galaxies came along this direction, the orientation of the DoS would be related to the infall direction as is the case for infalling dark matter halos along filaments. The major difference is that subhalos can come at any angle along the filament and thus in general do not have correlated orbits, whereas tidal dwarfs do.

In summary, this paper presents a detailed investigation of recent claims that the dSph satellites of the MW entered the MW system as part of a galaxy group surrounding the Magellanic Clouds, or as a stand-alone dwarf group. By considering the observed properties of the known groups of galaxies within about 6 Mpc of the MW, it is concluded that all these systems are too spatially extended to be the progenitors of the disklike MW satellite distribution. Because the observed galaxy groups are not compact, the recent claims that dwarf galaxies within such groups would be able to retain, or even reaccrete, gas are rendered unlikely. Tentative evidence for an intermediate-scale filamentary structure in the distribution of nearby galaxy groups is brought up which could indicate the direction of infall of a galaxy which interacted with the young MW such that TDGs formed in the expanding tidal arms producing a system of dSph satellite galaxies that remain correlated in phase space.

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REFERENCES

Bailin, J., & Steinmetz, M. 2005, ApJ, 627, 647
Besla, G., Kallivayalil, N., Hernquist, L., Robertson, B., Cox, T. J., van der Marel, R. P., & Alcock, C. 2007, ApJ, 668, 949
Bullock, J. S., Kolatt, T. S., Sigad, Y., Somerville, R. S., Kravtsov, A. V., Klypin, A. A., Primack, J. R., & Dekel, A. 2001, MNRAS, 321, 559
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R. J., Paturel, G., & Fouque, P. 1991, Third Reference Catalogue of Bright Galaxies, Vols. 1–3 (Berlin: Springer)
Drimond, J., Kuijken, M., Madau, P., Zemp, M., Moore, B., Potter, D., & Stadel, J. 2008, Nature, 454, 735
Dinescu, D. I., Keeney, B. A., Majewski, S. R., & Girard, T. M. 2004, AJ, 128, 687
D’Onghia, E., & Lake, G. 2008, ApJ, 686, L61
Fall & Maier, E. 2006, ApJ, 651, 167
Gilmore, G., Wilkinson, M. I., Wyse, R. F. G., Klypin, J. T., Koch, A., Evans, N. W., & Grebel, E. K. 2007, ApJ, 663, 948
Ibata, R. A., Gilmore, G., & Irwin, M. J. 1994, Nature, 370, 194
Ibata, R. A., Wyse, R. F. G., Gilmore, G., Irwin, M. J., & Suntzeff, N. B. 1997, AJ, 113, 634
Irwin, M. J., Bumclark, P. S., Bridgeland, M. T., & McMahon, R. G. 1990, MNRAS, 244, 16
Kallivayalil, N., van der Marel, R. P., & Alcock, C. 2006a, ApJ, 652, 1213
Kallivayalil, N., van der Marel, R. P., Alcock, C., Axelrod, T., Cook, K. H., Drake, A. J., & Geha, M. 2006b, ApJ, 638, 772
Karachentsev, I. D., Karachentseva, V. E., Huchtmeier, W. K., & Makarov, D. I. 2004, AJ, 127, 2031
Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Kuebe, A., Gill, S. P. D., Gibson, B. K., Lewis, G. F., Ibata, R. A., & Dopita, M. A. 2004, ApJ, 603, 7
