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Excerpt

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History of the Local Group

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It is suggested that M31 was created by the early merger and subsequent violent relaxation of two or more massive metal-rich ancestral galaxies within the core of the Andromeda subgroup of the Local Group. On the other hand, the evolution of the main body of the Galaxy appears to have been dominated by the collapse of a single ancestral object that subsequently evolved by capturing a halo of small metal-poor companions. It remains a mystery why the globular cluster systems surrounding galaxies like M33 and the LMC exhibit such striking differences in evolutionary history. It is argued that the first generation of globular clusters might have been formed nearly simultaneously in all environments by the strong pressure increase that accompanied cosmic reionization. Subsequent generations of globulars may have formed during starbursts that were triggered by collisions and mergers of gas-rich galaxies.

The fact that the [G]alactic system is a member of a group is a very fortunate accident. Hubble (1936, p. 125)

1. Introduction

According to Greek mythology, the goddess of wisdom, Pallas Athena, clad in full armor, emerged from Zeus's head after Hephaestus split it open. In much the same way the Local Group sprang forth suddenly, and almost complete, in Chapter VI of *The Realm of the Nebulae* (Hubble 1936, pp. 124–151). Hubble describes the Local Group as “a typical small group of nebulae which is isolated in the general field.” He assigned (in order of decreasing luminosity) M31, the Galaxy, M33, the Large Magellanic Cloud, the Small Magellanic Cloud, M32, NGC 205, NGC 6822, NGC 185, IC 1613 and NGC 147 to the Local Group, and regarded IC 10 as a possible member. In the two-thirds of a century since Hubble's work, the number of known Local Group members has increased from 12 to 36 (see Table 1) by the addition of almost two dozen low-luminosity galaxies. Recent detailed discussions of individual Local Group galaxies are given in Mateo (1998), Grebel (2000) and van den Bergh (2000a). Hubble (1936, p. 128) pointed out that investigations of the Local Group were important for two reasons: (i) “[T]he members have been studied individually, as the nearest and most accessible examples of their particular types, in order to determine the[ir] internal structures and stellar contents,” and (ii) “the [G]roup may be examined as a sample collection of nebulae, from which criteria can be derived for further exploration.”

Small galaxy groups, like the Local Group, are quite common. From inspection of the prints of the *Palomar Sky Survey*, van den Bergh (2002a) has estimated that 16% of nearby galaxies are located in such small groups. Hubble (1936, p. 128) emphasized that: “The groups [such as the Local Group] are aggregations drawn from the general field, and are not additional colonies superposed on the field.” From its observed radial velocity dispersion of $61 \pm 8 \text{ km s}^{-1}$, the Local Group is found to have a virial mass of $(2.3 \pm 0.6) \times 10^{12} M_{\odot}$ (Courteau & van den Bergh 1999). The zero-velocity surface of the Local Group has a radius of $1.18 \pm 0.15 \text{ Mpc}$, but $\sim 80\%$ of the Local Group members are actually situated within 0.4 Mpc of the barycenter of the Local Group, which is located between M31 and the Galaxy. From its virial mass and the integrated

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Name	Alias	DDO Type†	D(kpc)	M_V
M31	NGC 224	Sb I- II	760	- 21.2
Milky Way	Galaxy	Sbc I- II:	8	- 20.9
M33	NGC 598	Sc II- III	795	- 18.9
LMC	...	Ir III- IV	50	- 18.5
SMC	...	Ir IV/IV- V	59	- 17.1
M32	NGC 221	E2	760	- 16.5
NGC 205	...	Sph	760	- 16.4
IC 10	...	Ir IV:	660	- 16.3
NGC 6822	...	Ir IV- V	500	- 16.0
NGC 185	...	Sph	660	- 15.6
IC 1613	...	Ir V	725	- 15.3
NGC 147	...	Sph	660	- 15.1
WLM	DDO 221	Ir IV- V	925	- 14.4
Sagittarius	...	dSph(t)	24	- 13.3
Fornax	...	dSph	138	- 13.1‡
Pegasus	DDO 216	Ir V	760	- 12.3
Leo A	DDO69	Ir V	800	- 12.2¶
SagDIG	...	Ir V	1180	- 12.0
Leo I	Regulus	dSph	250	- 11.9
And I	...	dSph	810	- 11.8
And II	...	dSph	700	- 11.8
Aquarius	DDO 210	V	1025	- 11.3
Pegasus II	And VI	dSph	815	- 10.5††
And V	...	dSph	810	- 10.2
And III	...	dSph	760	- 10.2
Cetus	...	dSph	775	- 10.2‡‡
Leo II	...	dSph	210	- 10.1
Pisces	LGS 3	dIr/dSph	620	- 9.8¶¶
Phoenix	...	dIr/dSph	395	- 9.8
Sculptor	...	dSph	87	- 9.8
Tucana	...	dSph	895	- 9.6
Cassiopeia	And VII	dSph	690	- 9.5
Sextans	...	dSph	86	- 9.5
Carina	...	dSph	100	- 9.4
Draco	...	dSph	79	- 8.6
Ursa Minor	...	dSph	63	- 8.5

† Uncertain values are marked by a colon (:)

‡ from Majewski et al. (2003)

¶ from Dolphin et al. (2002)

from Lee & Kim (2000)

†† from Pritzel et al. (2002)

‡‡ from Whiting et al. (1999)

¶¶ from Miller et al. (2001)

from Walker (2003)

TABLE 1. Members of the Local Group

luminosity of Group members of $4.2 \times 10^{10} L_{\odot}$, the dynamical mass-to-light ratio of the Local Group is found to be $M/L_V = 44 \pm 12$ in solar units. Such a high M/L value is an order of magnitude larger than the mass-to-light ratio in the solar neighborhood of the Galaxy. This supports the conclusion by Kahn & Woltjer (1959) that the mass of the Local Group is dominated by invisible matter.

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2. Neighborhood of the Local Group

The Local Group is situated in the outer reaches of the Virgo supercluster. The nearest neighbor of the Local Group is the small Antlia group (van den Bergh 1999a). This tiny cluster is located at a distance of only 1.7 Mpc from the barycenter of the Local Group, i.e., well beyond the zero-velocity surface of the Group. The Antlia group has a mean radial velocity of $+114 \pm 12 \text{ km s}^{-1}$. The number of galaxies brighter than $M_V = -11.0$ in the Local Group is 22, compared to only four such objects in the Antlia group. However, because the Antlia group contains no supergiant galaxies like M31 and the Milky Way system, its integrated luminosity is ~ 150 times smaller than that of the Local Group. Since the Local Group is a relatively small cluster, this result suggests that clusters of galaxies have a range in luminosities (and masses?) that extend over at least four orders of magnitude.

At a distance of ~ 3.9 Mpc, the Centaurus group—which contains M83 (NGC 5236) and Centaurus A (NGC 5128)—is the nearest massive cluster (van den Bergh 2000b). If one assumes NGC 5128 and NGC 5236 to be members of a single cluster, one obtains a total virial mass of $1.4 \times 10^{13} M_\odot$ and a zero-velocity radius of 2.3 Mpc for the Centaurus group. In other words, the zero-velocity surfaces of the Centaurus group and the Local Group would almost touch each other. However, Karachentsev et al. (2002) conclude that the galaxies surrounding NGC 5128 and M83, respectively, actually form dynamically distinct clusterings. If that is indeed the case, the total mass of these clusters is reduced to only $3 \times 10^{12} M_\odot$, and the radius of the zero-velocity surface around Cen A is less than 1.3 Mpc.

A second massive nearby cluster contains IC 342 and the highly obscured elliptical Maffei 1. McCall (1989) concluded that “it is likely that IC 342 and Maffei 1 had a significant impact on the past dynamical evolution of the major members of the Local Group.” More recently, Fingerhut et al. (2003a,b) have, however, found that the Galactic absorption in front of Maffei 1 is lower than was previously believed. As a result, the distances to Maffei 1 and its companions are too large for these objects to have had significant dynamical interactions with individual Local Group members since the Big Bang.

If the peculiar velocities of galaxies are induced by gravitational interactions, then one might expect massive field galaxies to have a lower velocity dispersion than dwarfs. Data on nearby field galaxies do not appear to support this expectation (Whiting 2003). Whiting (2003) finds the mean radial velocity dispersion among field galaxies within 10 Mpc to be 113 km s^{-1} . A much lower dispersion of $\sim 30 \text{ km s}^{-1}$ for the local Hubble flow has, however, been found by Karachentsev et al. (2002). It is noted in passing that the former value appears to be significantly larger than the radial velocity dispersion of $61 \pm 8 \text{ km s}^{-1}$ found by Courteau & van den Bergh (1999) within the Local Group itself.

3. Subclustering in the Local Group

To first approximation, the Local Group is a binary system with massive clumps of galaxies centered on M31 and on the Galaxy. van den Bergh (2000, p. 290) estimates a mass $M(A) = (1.15\text{--}1.5) \times 10^{12} M_\odot$ for the Andromeda subgroup of the Local Group compared to $M(G) = (0.46\text{--}1.25) \times 10^{12} M_\odot$ for the Galactic subgroup. Sakamoto, Chiba & Beers (2003) have given somewhat higher mass estimates. If Leo I is included, they find $M(G) = (1.5\text{--}3.0) \times 10^{12} M_\odot$, compared to $M(G) = (1.1\text{--}2.2) \times 10^{12} M_\odot$ if it is assumed that Leo I is not a member of the Galactic subgroup. Recent proper motion observations by Piatek et al. (2002) suggest that the Fornax dwarf spheroidal galaxy may

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Environment	Sph+dSph	dSph/dIr	Ir
Isolated	1	2	6
?	1	1	1
In subcluster	15	0	0

TABLE 2. Environments of dwarf members of the Local Group

not, as previously thought, be a distant satellite of the Galaxy. Instead, the data appear to indicate that Fornax is a free-floating member of the Local Group that is presently near periGalacticon. Within each of the two main Local Group subclusters there are additional subclumps such as the M31 + M32 + NGC 205 triplet, the NGC 147 + NGC 185 binary, and the LMC + SMC binary. For the entire Local Group one finds, at the 99% confidence level, that low-luminosity early-type dSph galaxies are more concentrated in subclumps than late-type dIr galaxies. In other words, most dIr galaxies appear to be free-floating members of the Local Group, whereas the majority (but not all) of dSph galaxies seem to be directly associated with either M31 or the Galaxy. It is not yet clear if the mean ages of the stellar populations in dSph galaxies are themselves a function of location. van den Bergh (1995) has tentatively suggested that star formation in dSph galaxies in the dense regions close to M31 and the Galaxy might typically have started earlier than star formation in remote dSph galaxies. The data in Table 2 show a strong correlation between the morphological types of faint galaxies with $M_V > -16.5$ (i.e., objects fainter than M32) and their environment. This dependence was first noticed by Einasto et al. (1974). Almost all Sph + dSph galaxies are seen to be associated with the two dense subclusters within the Local Group, whereas most Ir galaxies appear to be more or less isolated Group members. It seems quite possible (cf. Skillman et al. 2003) that the faint dIr and dSph galaxies have similar progenitors, and the observed differences between them are due to environmental factors favoring gas loss (from those dwarfs) that occurred in dense environments, i.e., near giant galaxies.

Within the Local Group, the M31, M32, M33 subgroup has a total luminosity $L_V = 3. \times 10^{10} L_\odot$. This is significantly greater than that of the subgroup centered on the Milky Way System, which has $L_V = 1.1 \times 10^{10} L_\odot$. The luminosities of the M31 and Galactic subgroups account for 71% and 24% of the total Local Group luminosity, respectively. It should, however, be noted that some uncertainty in the luminosity ratio of M31 to that of the Galaxy is introduced by the fact that both of these systems are viewed edge-on. As a result, the internal absorption corrections (which may be quite large) are uncertain. Nevertheless, the notion that M31 is more massive than the Galaxy receives some support from the observation that M31 appears to have 450 ± 100 globular clusters, compared to only 180 ± 20 such clusters associated with the Galaxy (Barmby et al. 2000). Furthermore, the bulge mass of M31 is $3.6 \times 10^{10} M_\odot$ (Freeman 1999), which is almost twice as large as the $2 \times 10^{10} M_\odot$ mass of the Galactic bulge. On the basis of these results one might expect the total mass of the M31 subgroup of the Local Group to be two or three times larger than that of the Galaxy subgroup. Surprisingly, this does not appear to be the case. Using radial velocity observations, Evans et al. (2000) conclude that: "There is no dynamical evidence for the widely held belief that M31 is more massive—it may even be less massive." Gottesman et al. (2002) also concluded from dynamical arguments that the mass of M31 "is unlikely to be as great as that of our own Milky Way." These authors even make the heretical suggestion that M31 might not have a massive halo at all! Either the well-known perfidy of small-number statistics has misled us about the relative

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masses of M31 and the Galaxy, or the mass-to-light ratio in the Milky Way system is much higher than that of the Andromeda galaxy. If the latter conclusion is correct, then one would have to accept the existence of significant galaxy-to-galaxy variations in the ratio of visible to dark matter among giant spirals.

4. The halos of M31 and the galaxy

It has been known for many years that the halo of M31 contains some globular clusters that are much more metal-rich than those in the Galactic halo (van den Bergh 1969). Perhaps the best known example is the luminous globular cluster Mayall II. Furthermore, the color-magnitude diagrams for individual M31 halo stars (Mould & Kristian 1986, Pritchett & van den Bergh 1988, Durrell, Harris & Pritchett 1994) all show that (i) halo stars have a wide range in metallicity, and (ii) the mean metallicity of stars in the halo of M31 is surprisingly high. The mean values of $[Fe/H]$ for M31 halo stars obtained by Mould & Kristian, by Pritchett & van den Bergh and by Durrell, Harris & Pritchett are $\langle [Fe/H] \rangle = -0.6, -1.0$ and -0.6 , respectively. (It is noted in passing that the halo of M31 does contain a metal-poor component which includes clusters such as Mayall IV, some RR Lyrae variables, and non-variable horizontal-branch stars; Sarajedini & Van Duyn 2001.) The observation that the stars in the halo of M31 appear, on average, to be much more metal-rich than those in the Galactic halo, suggests that these two giant spiral galaxies had quite different evolutionary histories (Durrell, Harris & Pritchett 1994). The higher metallicity of M31 halo stars indicates that the building blocks of the Andromeda halo had much higher masses than those of the Galactic halo. Simulations of Murali et al. (2002) show that a significant fraction of the mass that was originally in such merging ancestral galaxies will end up as intergalactic debris and, presumably, also in an extended halo of the final merged object.

An independent check on the metallicities of M31 giants is provided by the recent spectroscopic observations undertaken by Reitzel & Guhathakurta (2002). Their spectra of stars in the halo of M31 have a mean metallicity of $\langle [Fe/H] \rangle = -1.3$. This value is significantly lower than that derived from photometric observations of stars in the halo of the Andromeda galaxy. A possible explanation for this difference is that insufficient correction was made for the fact that old metal-rich red giants are fainter (and therefore more difficult to observe) than are old metal-poor giants. Non homogeneity of the Andromeda halo might also have contributed to the observed difference in the mean metallicities derived from photometry and spectroscopy. For example, Reitzel & Guhathakurta (2002) find four stars of solar metallicity in the halo of M31. They suggest that these objects might represent metal-rich debris from an accretion event. Other evidence for such accretion events is provided by Ibata et al. (2001) and Ferguson et al. (2002). Recently, Yanny et al. (2003) also found possible evidence for such a tidal stream in the Galaxy, located beyond the plane of the Milky Way at a distance of ~ 20 kpc from the Galactic center.

An interesting clue regarding the origin of the difference between the Andromeda and the Galactic halos is provided by the observations of Pritchett & van den Bergh (1994; see Figure 1), which show that M31 has an $R^{1/4}$ profile out to ~ 20 kpc from its nucleus. Such a structure is likely to have resulted from violent relaxation. This suggests that the overall morphology of the Andromeda galaxy was determined by violent relaxation resulting from the early merger of two (or more) massive metal-rich ancestral objects. On the other hand, the main body of the Milky Way system may have been assembled à la Eggen, Lynden-Bell & Sandage (1964), with its metal-poor halo forming via late infall and capture of "small bits and pieces" (Searle & Zinn 1978). However, it appears that these

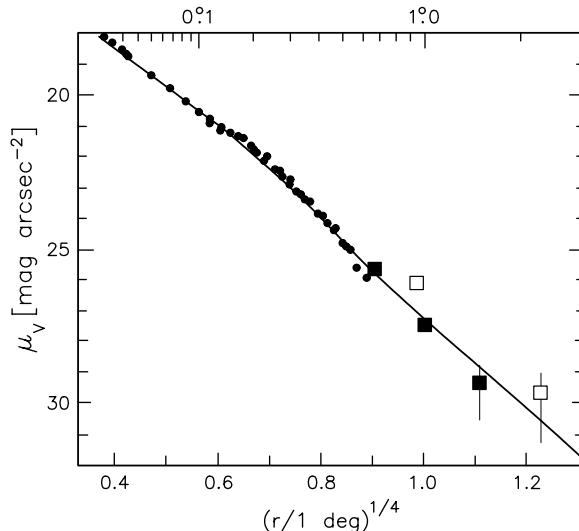


FIGURE 1. Profile of M31 derived from star counts. The figure shows that an $R^{1/4}$ law provides a reasonable fit to the observations. This favors the interpretation that M31 was formed from violent relaxation following mergers.

fragments differed in a rather fundamental way from those producing dwarf spheroidal galaxies. Shetrone, Côté, & Sargent (2001) find that dSph galaxies are iron-rich and have $0.02 \leq [\alpha/\text{Fe}] \leq 0.13$, compared to typical Galactic values of $[\alpha/\text{Fe}] \sim 0.28$ dex over the same range of metallicities. This shows that the bulk of the Galactic halo stars cannot have formed in dwarf spheroidal galaxies that subsequently disintegrated. In particular, Fulbright (2002) finds that less than 10% of local metal-poor stars with $[\text{Fe}/\text{H}] < -1.2$ have α -to-iron abundance ratios similar to those found in dSph galaxies. More generally, Tolstoy et al. (2003) conclude that the observed element abundance patterns make it difficult to form a significant proportion of the stars observed in our Galaxy in the small galaxies that subsequently merged to form the disk, bulge, and inner halo of the Milky Way.

Bekki, Harris & Harris (2003) studied the distribution of stars of various metallicities after the merger of two spirals. However, their model is not likely to be applicable to the early merger of the ancestral objects of M31, because extended disks would be destroyed by frequent tidal interactions at large look-back times. *Hubble Space Telescope* images show that galaxies with obvious disks mostly have $z < 1.5$, whereas the vast majority of the objects seen at $z > 1.5$ appear to have either compact or chaotic morphologies (van den Bergh 2002b). So the Bekki et al. model, in which extended disks merge, is probably inappropriate for galaxies at $z > 1.5$, i.e., for mergers that took place more than nine Gyr ago.

In their pioneering study of the metallicities of individual stars in galactic halos, Mould & Kristian (1986) also observed stars in the halo of the late-type spiral M33. Their color-magnitude diagram suggested that the halo of M33 was very metal-poor and had $\langle [\text{Fe}/\text{H}] \rangle = -2.2$. This value is more than an order of magnitude lower than that for stars in the halo of the Andromeda galaxy.

In summary, M31 may have formed from the early merger of the two or three most massive galaxies in the core of the Andromeda subgroup of the Local Group. The less massive Andromeda companions, such as M32 and NGC 205, may represent objects in

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the core of the Andromeda subgroup which had such low masses they managed to survive individually.

5. History of globular cluster systems

Due to differences in evolutionary history, the halo of M31 contains relatively metal-rich globular clusters, whereas the Galactic halo does not. Another difference between the M31 and Galactic globular cluster systems has been noted by Rich et al. (2002), who find that M31 does not appear to contain globular clusters with extremely blue horizontal branches, such as M92 in the Galactic halo. Another major difference between globular cluster systems is provided by M33 and the LMC. These two late-type disk galaxies have comparable luminosities ($M_V = -18.9$ and -18.5 , respectively), but radically different globular cluster systems. Surprisingly, the LMC globulars, which are both very old and quite metal-poor, appear to have disk kinematics (Schommer et al. 1993). On the other hand, the metal-poor globular clusters associated with M33 seem to have halo-like kinematics (Schommer et al. 1991). Sarajedini et al. (1998) found that eight out of ten globular clusters in their M33 halo sample had significantly redder horizontal branches than Galactic globulars of similar metallicity. This difference might be interpreted as a second parameter effect. Alternatively, and perhaps more plausibly, the M33 globulars may be a few Gyr younger than their Galactic counterparts. In the latter interpretation, the M33 halo globular clusters exhibit an unexpectedly large age dispersion of ~ 3 –5 Gyr. It is presently a mystery why the M33 halo globular clusters would have formed a few Gyr later than typical Galactic halo and LMC disk globulars. Some light might eventually be shed on these questions by observations of the radial velocities of RR Lyrae stars in the LMC, and perhaps also in the near future, of RR Lyrae stars in M33. The main differences between the globular cluster systems of M33 (Sc) and the Galaxy (Sbc) could perhaps be understood (van den Bergh 2002b) by assuming that late-type galaxies take significantly longer to arrive at their final morphology than do spirals of earlier morphological types. However, the great age of the LMC cluster system appears to conflict with this simple explanation. The observations of Mould & Kristian (1986) appear to show that the field stars in the halo of M33 are extremely metal-poor and have $\langle [\text{Fe}/\text{H}] \rangle = -2.2$. It would be important to confirm this result by new photometry and to compare this value with the mean metallicity of stars in the outer halo of the Large Magellanic Cloud.

Not unexpectedly, the majority of Local Group dwarf galaxies are surrounded by small families of metal-poor globular clusters. However, it is puzzling that the Sagittarius dwarf has one globular cluster companion (Terzan 7, $[\text{Fe}/\text{H}] = -0.36$) that is quite metal-rich. How could such a relatively high metallicity have been built up within a dwarf galaxy? The only other Galactic halo ($R_{\text{gc}} > 10$ kpc) globular clusters known to have metallicities higher than $[\text{Fe}/\text{H}] = -1.0$ are Pal 1 and Pal 12. The latter object is, itself, suspected of also being associated with the disintegrating Sagittarius dwarf (Irwin 1999). This speculation is supported by the observations of Martínez-Delgado et al. (2002), who have found that Pal 12 is possibly embedded in tidal debris of the Sagittarius dwarf.

Rosenberg et al. (1998a,b) have also shown that the cluster Pal 1 is significantly younger than most other Galactic globular clusters. It is presently not clear which kind of evolutionary scenarios would allow halo clusters like Pal 1 and Pal 12 to attain such relatively high metallicities. From its present luminosity and morphological type, the dwarf elliptical galaxy M32 would have been expected to be embedded in a swarm of 10–20 globular clusters. It is therefore puzzling that not a single globular cluster appears to be associated with this galaxy. Perhaps some of the innermost M32 clusters were dragged into its compact luminous nucleus by dynamical friction. Also, loosely bound outer globulars

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that were originally associated with M32 might have been detached by tidal interactions with the main body of M31. Such detached M32 clusters would remain in the halo of M31 and might be recognized by being unusually compact. It would be very worthwhile to undertake a systematic search for such M32 clusters with small R_h values in the halo of M31.

For the vast majority of galaxies, the specific globular cluster frequency S is less than 10 (Harris & van den Bergh 1981). However, the Fornax dwarf, which has five globulars associated with it, has $13 < S < 26$. Recent work by Kleyna et al. (2003) appears to indicate that the Ursa Minor dwarf may have an even higher S value. If a dynamically cold clustering of stars that these authors find in UMi is a globular cluster (or a disintegrated cluster), then $S \sim 400$ for the UMi system. Taken at face value, this result suggests that the fraction of the light of dwarf spheroidals in the form of globular clusters may be much higher in dwarf spheroidal galaxies than it is in more luminous (massive) systems.

If the Milky Way system had collapsed in the fashion advocated by Eggen, Lynden-Bell & Sandage (1962), but with some gaseous dissipation, then one would have expected the stars and globular clusters in the Galactic halo to exhibit a radial metallicity gradient. On the other hand, the halo of the Milky Way system would not be expected to have such a metallicity gradient if, as envisioned by Searle & Zinn (1978), it had formed by the accretion of many “bits and pieces.” Using the 1999 version of the globular cluster catalog of Harris (1996), van den Bergh (2003) found a possible hint for the existence of such a radial metallicity gradient among Galactic halo ($R_{gc} > 10$ kpc) globular clusters. However, the reality of this a gradient is not supported by the more recent data contained in the 2003 version of Harris’s catalog. On the other hand, the clusters in the main body of the Galaxy, i.e., those with $R_{gc} < 10$ kpc, do appear to show a radial abundance gradient. Globulars at $R_{gc} < 4.0$ kpc are, on average, found to be more metal-rich than those having $4.0 \leq R_{gc} < 10$ kpc. A Kolmogorov-Smirnov test shows that there is only a 4% probability that the metallicities of these inner and outer globular clusters samples were drawn from the same parent population. Taken at face value, the existence of a Galactic metallicity gradient between 4 kpc and 10 kpc favors the suggestion that the ELS model provides an adequate description of the formation of the main body of the Galactic halo, whereas the SZ model predictions agree with the observed lack of a metallicity gradient in the region with $R_{gc} > 10$ kpc.

It is a curious (and unexplained) fact that the distribution of flattening values of globular clusters differs significantly from galaxy to galaxy. Both open and globular clusters in the LMC are, for example, generally more flattened than their Galactic counterparts. Furthermore, the luminous clusters in the Large Cloud are typically more flattened than the less luminous ones (van den Bergh 1983). Finally, it is of interest to note that the most luminous globular clusters in many Local Group galaxies also seem to be among the most flattened. Examples are the globular Mayall II ($\epsilon = 0.22$) in M31, ω Centauri ($\epsilon = 0.19$) in the Galaxy, and NGC 1835 ($\epsilon = 0.21$) in the LMC.

6. The luminosity function of the Local Group

The presently known members of the Local Group exhibit a flat luminosity function with slope $\alpha = -1.1 \pm 0.1$ (Pritchet & van den Bergh 1999). This value is significantly lower than the slope $\alpha = -1.8$ that is predicted by the cold dark matter theory (Klypin et al. 1999). The low frequency of faint Local Group dwarfs has been confirmed in a recent hunt for new faint Local Group members by Whiting, Hau & Irwin (2002). This observed deficiency of faint LG members suggests that many of the progenitors of low mass galaxies were destroyed before they had a chance to form significant numbers of

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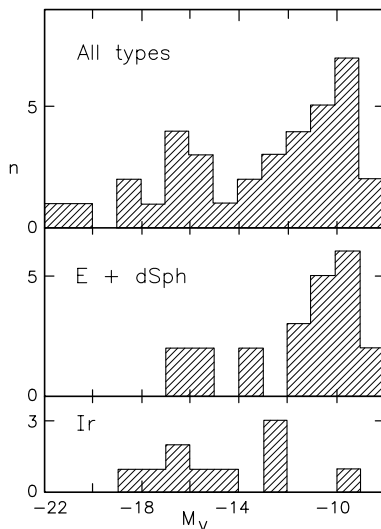
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FIGURE 2. Luminosity function of the Local Group. The data suggest, but do not prove, that dIr luminosity distribution is less steep than that for dSph galaxies.

stars. Alternatively, it might be assumed that the missing faint galaxies can be identified with compact high-velocity clouds. However, Maloney & Putman (2003) have recently shown that such objects, if they were located at distances of ~ 1 Mpc, would be largely ionized. Therefore, these authors conclude that the compact high-velocity clouds are not at cosmologically significant distances, but that they are instead associated with the Galactic halo. All attempts to search for evidence of star formation in compact high-velocity clouds (e.g., Simon & Blitz 2002) have so far remained unsuccessful. It is therefore assumed that the deficiency of faint Local Group members is real. Figure 2 appears to show (van den Bergh 2000a, p. 281) that the luminosity function of dSph galaxies in the Local Group is steeper than for dIr galaxies. This conclusion should, however, be regarded as provisional, because a Kolmogorov-Smirnov test shows the difference between the luminosity distributions of Local Group dSph and dIr galaxies is only significant at the 75% confidence level. If the luminosity function of dSph galaxies is, indeed, steeper than for dIr galaxies, then future discoveries are most likely to turn up very faint dSph (rather than dIr) members of the Local Group. It would clearly be very important to undertake sky surveys in two (or more) colors to search for the signatures of the color-magnitude diagrams of extremely faint (and so far undiscovered) resolved dwarf members of the Local Group.

Three distinct explanations might be invoked to account for the apparent excess of faint dSph galaxies among presently known Local Group members: (i) Perhaps gas was more likely to escape from faint (low-mass) galaxies than from more massive objects. As a result, low-mass galaxies would most often end up as gas-free dSph galaxies. (ii) Alternatively, the mass spectrum with which galaxies form might depend on environmental density in such a way that high density regions (i.e., the neighborhood of M31 and the Galaxy) form a larger fraction of low-mass objects (the majority of which end up as dSph galaxies). The latter assumption would be consistent with the work of Trentham et al. (2001) and Trentham & Tully (2003), who found that the galaxian luminosity function of the dense Virgo cluster is much steeper than for the less dense Ursa Major cluster and the Local Group. On the other hand, the view that dense regions produce galaxies with steep galaxian luminosity functions appears to conflict with the result of Sabatini

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et al. (2003), who find that the Virgo cluster luminosity function seems to be steeper in the low density outer regions than it is in the high density core of this cluster. This observation might, however, be accounted for by assuming that tides preferentially destroy fragile dwarfs in the cores of dense clusters. (iii) Finally, and perhaps most plausibly, the gas in the progenitors of the missing dwarfs might have been photoevaporated during reionization.

7. Morphological evolution of Local Group members

It is difficult to tease out information on the morphological evolution of galaxies from the distribution of stars of various ages. The central bulges of giant spirals, such as M31 and the Galaxy, are dominated by old stars. This supports the notion that these objects were built up inside out, with their bulges forming first and the disk possibly being accreted at a later time. It would be very important to establish how old the first (presumably quite metal-poor) generation of Galactic disk stars is. This problem is made more intractable because such thin disk stars have to be disentangled from stars that are physically associated with—and embedded within—an older thick disk population. In fact, tidal interactions might pump energy into (and hence thicken) an initially thin disk of very metal-poor stars. *Hubble Space Telescope* observations of galaxies at large look-back times suggest that most disk star formation occurs at $z \lesssim 1.5$, i.e., during the last 9 Gyr (van den Bergh 2002b). One reason for the paucity of disks at larger redshifts is, presumably, that such extended structures would be destroyed by tidal forces during the frequent encounters between galaxies at high redshifts. From the disk kinematics of two slightly metal-poor stars, Liu & Chaboyer (2000) find a thin disk age of 9.7 ± 0.6 Gyr. Such an age is consistent with the ages of spiral disks, inferred from the fact that the *HST* images of distant galaxies start to show obvious disks at $z \sim 1.5$.

Since bars are generally assumed to have formed from global instabilities in disks, one would not expect to see barred galaxies at $z > 1.5$. If bars cannot form from initially chaotic protodisks, then bar formation might be delayed to even smaller look-back times. This suspicion appears to be confirmed by observations which seem to suggest that the frequency of barred galaxies declines precipitously beyond redshifts of $z \sim 0.7$ (van den Bergh et al. 1996, 2002). If this conclusion is correct, then one would expect the Bar of the LMC to be younger than 6 Gyr. This conclusion is consistent with (but not proved by) the observation that bursts of star formation occurred in the Bar of the Large Cloud 4–6 Gyr and 1–2 Gyr ago (Smecker-Hane et al. 2002).

8. The history of star and cluster formation

Almost all Local Group galaxies are found to contain some very old stars like RR Lyrae variables. This shows that these galaxies started to form stars quite early in the history of the Universe, i.e., more than ~ 10 Gyr ago. The best candidate for a “young” Local Group member is the dwarf irregular Leo A. However, Dolphin et al. (2002) discovered a few RR Lyrae variables in this galaxy which have ages > 9 Gyr. Furthermore, recent observations by Schulte-Ladbeck et al. (2002) show that this object also contains some metal-poor red horizontal branch stars. This clearly demonstrates that Leo A is not a young galaxy.

M32 and many of the Local Group dSph galaxies have not experienced recent star formation. On the other hand, the gas-rich spiral and irregular Group members are still forming stars at a significant rate. Qualitative data on the past rate of star formation in such galaxies can be obtained from their integrated colors and the intensity ratios