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Chemical Evolution of the Old Stellar Populations of M31

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Abstract

The stellar populations concept was developed based on Baade's studies of the central bulge of the Andromeda Galaxy, M31. Yet, the Andromeda system now appears to be anything but typical. Deep imaging reveals the outer halo to be a flattened system of complex tidal filaments roughly aligned with the disk major axis. Studies of the field remote from the nucleus find a metal-rich population that shows little variation in its mean abundance or distribution in projected locations ranging from 5 to 35 kpc from the nucleus. Every study to date confirms that the halo population is metal-rich, at [Fe/H]≈ -0.5, with a tail extending to lower metallicity. The halo within 20 kpc cannot be composed of disrupted dwarf spheroidal satellites of M31, which are very metal-poor and have well-populated blue horizontal branches. The stars in the interaction streams of M31 are more metal-poor, with a smaller abundance spread than the disk stars.

The age distribution of one deep halo field has been constrained from *HST* imaging, which shows that it has an old, metal-poor population, but also an equal population of 6–11 Gyr old, metal-rich stars. While the halo may be intermediate age, the bulge and a large fraction of the globular clusters appear to be old and similar to comparable populations in the Milky Way.

We show that M31 lies in the expected location on a plot of halo abundances as a function of total galaxy luminosity. While this relationship may be understood as implying that a metal-enriched wind controls chemical evolution, it is difficult to understand how a simple closed-box model with wind outflow could be consistent with the presence of a significant age range in the halo. The complexity present in the old populations of M31 stands to remind us how complicated the history of distant galaxies might be.

1.1 Introduction

It is indeed appropriate to consider the chemical evolution of M31 at this Carnegie Centennial Symposium. As is well known, Baade's investigations of M31 led directly to the development of the stellar populations paradigm (Baade 1944). Hubble's identification of a Cepheid variable in M31 certified its classification as an extragalactic system.

Baade might be surprised to know that while the stellar populations of M31 helped to develop the fundamental Population I and II paradigm, only within the last few years has M31 been revealed to be a system of remarkable complexity. M31 has a factor of 3 more globular clusters than the Milky Way, and the nature of the stellar halo is unclear. One sees a widespread metal-rich stellar population, but there is also clear evidence of tidal streams. The metal-rich population in the halo is intermediate age. Had this article been written a year earlier, it likely would have emphasized a relatively well-understood picture of chemical evolution driven by star formation and metal-enriched winds. This simplified picture is no longer appropriate for M31. The proximity of M31 permits studies of detail sufficient to uncover its peculiarities. Within the next decade, there is the potential for a wide-field imaging program in M31 from space, as well as the use of 10 m-class telescopes to measure detailed abundances of giants in the old populations. There is little doubt that more surprises are in store.

The impact of other Carnegie scientists on the subject of chemical evolution is well known, but bears mention because of the occasion of this meeting. The two dominant constructs for chemical evolution are the so-called ELS (Eggen, Lynden-Bell, & Sandage 1962) picture of prompt initial enrichment, violent relaxation, and an early burst of star formation and chemical evolution. The other construct is the so-called Searle-Zinn hypothesis, in which massive systems are built out of the merged remnants of low-mass systems (Searle & Zinn 1978). Sandage and Searle, both Carnegie astronomers, played a central role in the development of these ideas. Zinn was a Carnegie Fellow at the time of the Searle & Zinn paper. Searle & Sargent (1972) also wrote the landmark paper in which the simple model of chemical evolution is fully developed. Carnegie scientists are, in large part, responsible for developing the foundations of the subject area to which this Symposium is devoted.

In this review I am considering the old stellar populations of the bulge, disk, and stellar halo. I will not consider the abundances of the disk H II regions or young stars; for these and other topics that I do not address here, the reader may refer to Hodge's (1992) comprehensive volume.

1.2 Overview

As the nearest bright spiral galaxy, one might hope that M31 would be typical of its class. At 770 Kpc distant, M31 is near enough to enable a wide range of studies on its populations. The initial studies of its globular cluster system appeared to fulfill that promise. While more numerous than that of the Milky, the M31 clusters divide into a centrally concentrated red (metal-rich) and blue (old, metal-poor group), just as is the case for the Milky Way clusters. Imaging of ~ 20 M31 globular clusters using *HST* has turned up no clear signature of an intermediate-age population and will be addressed more in the next section. At the time of this writing, the main sequence turn-off has been reached in one M31 globular cluster (G312) and an age determination is underway (Brown et al. 2004).

Early investigations of the halo abundance distribution function (Durrell, Harris & Pritchet 1994; Rich et al. 1996a, b) find that the halo is remarkably metal-rich, about -0.6 dex, with an abundance distribution that roughly resembles that predicted from the "simple model" of chemical evolution (Searle & Sargent 1972). In the context of these observations, one could imagine that the halo and old globular clusters formed early, followed by a dissipative starburst giving rise to the inner disk and bulge.

The discovery of the giant stream (Ibata et al. 2001; Fig. 1.1) and its extent in the deep M31 halo might cause one to abandon hope for a simple chemical evolution model for the halo. The presence of intermediate-age, metal-rich stars in the M31 halo (discussed further in §1.4.2) shows that the old populations of M31 are complex, but that a description of their chemical evolution must defy any orderly or simple description.

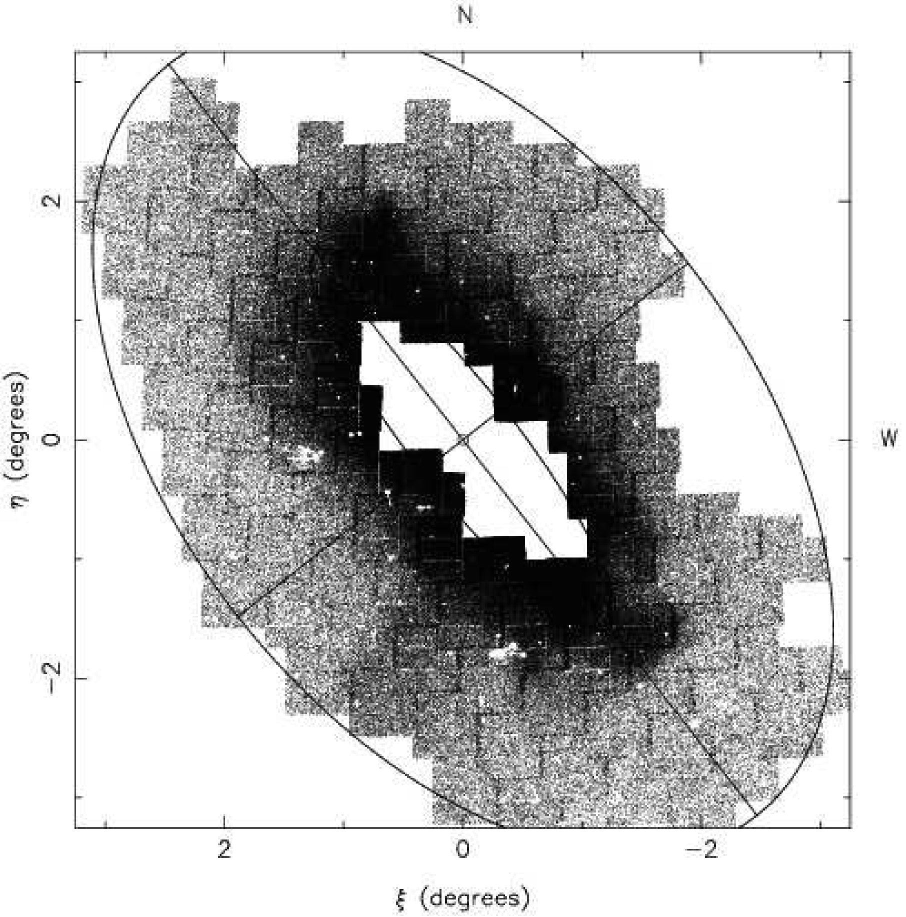

Fig. 1.1. This figure (Ferguson et al. 2002) shows the complex structure of the halo of M31, including the giant stream of Ibata et al. (2001) projecting on the lower left (SE direction). The complex structure along the SW major axis is near the globular cluster G1, although stars in that location do not share its radial velocity (§1.4.3 and Fig. 1.8; Reitzel, Guhathakurta, & Rich 2004). Projected onto the sky, the full extent of M31 and the Andromeda dwarfs spans roughly 10 degrees; were the eye sensitive to extreme low surface brightness, the halo of M31 would appear as large as the the Large Magellanic Cloud. Do these structures, the disk, and the smooth halo have differing star formation histories?

The origin of the most distant populations in M31 remains unclear. In one remote field roughly 34 kpc distant on the major axis, the kinematics of the population appears consistent with a disk origin. On the other hand, the averaged star counts at large distances fit a smooth radial falloff. The question of whether the remote populations are dominated by the cumulative debris of dissolved stellar systems (Côté et al. 2000a) or by the early formation history of M31 must ultimately be settled by further investigations.

Our survey of M31 begins by considering the well-studied globular cluster system (§1.3).

Following, §1.4 addresses the age, composition, and evolution of the halo. Section 1.4.2 presents the deepest *HST* imaging ever done in M31, while §1.4.3 analyzes a remote field on the major axis that appears to be dominated by the M31 disk. The dwarf satellites of M31 are discussed in §1.5, and §1.6 concerns the bulge of M31. In §1.7, we relate the M31 halo to the halo populations of other edge-on spiral galaxies. Section 1.8 summarizes this review and seeks a vision of chemical evolution for the old populations in M31.

1.3 Globular Clusters

The globular cluster system is the old stellar population of M31 that most closely resembles that of the Milky Way (Fig. 1.2). Based on *HST* color-magnitude diagrams reaching below the horizontal branch (Ajhar et al. 1996; Fusi Pecci et al. 1996; Rich et al. 1996b) the ~ 20 clusters with such deep color-magnitude diagrams appear to be as old as Milky Way globular clusters, with a similar primary strong correlation between horizontal branch morphology and metallicity. While an extended giant branch consisting of luminous carbon stars would likely have been detected in optical imaging and in the infrared (Stephens et al. 2001), no evidence for such an intermediate-age population is seen in resolved clusters. *HST* imaging of M31 globular clusters to date finds no evidence for extended giant branches, but the asymptotic giant branch (AGB) constrains less well the age of metal-rich populations (Guarnieri et al. 1998). Rich et al. (1996b) used WFPC2 to image the luminous globular cluster G1 at 1 μm, and infrared images have also been obtained (Stephens et al. 2001). If G1 had an extended AGB, we might (applying the fuel consumption theorem; Renzini & Buzzoni 1986) have seen upwards of 20 bright AGB stars.

Global studies of the cluster system, reaching back to Elson & Walterbos (1988), find no indication for a major subpopulation of intermediate-age or young clusters, such as is seen in the Magellanic Clouds. While the presence of a blue horizontal branch is *prima facie* evidence for an old stellar population, the discovery of candidate RR Lyrae variables in four M31 globular clusters with blue horizontal branches (Clementini et al. 2001) is reassuring.

A new approach by Jiang et al. (2003) fits multicolor photometry of the globular clusters to model spectral energy distributions. They confirm that a population of clusters as old as those in the Milky Way halo is present, but they also identify intermediate-age candidates. They argue further that the metal-rich clusters might be measurably younger than the metal-poor clusters. This approach is promising, but might be affected by the presence or absence of a blue horizontal branch, which is seen in some old, metal-rich clusters in the Milky Way (Rich et al. 1997). If infrared photometry and line strength measurements were to be added and included in the constraints, and the results were further calibrated using actual color-magnitude diagrams, this method might prove powerful in M31 and more distant galaxies.

As populations reach near 10 Gyr in age, relative age-related differences in their colors and spectra become subtle, and trace populations such as the blue horizontal branch or blue stragglers can affect the derived parameters. Beasley et al. (2004) fit Lick indices measured from high-quality spectra of 30 globular clusters using the population models of Thomas, Maraston, & Bender (2003). They find a subgroup of 13 metal-rich (> -1 dex) globular clusters consistent with 5 Gyr age. They confirm some of the Burstein et al. (1984) clusters with strong $H\beta$ but rely on other indices for their age constraint. However, their method gives an age of 7 ± 3 Gyr for the bulge of M31, and 3 ± 1.5 Gyr for M32, while the bright AGB stars required for such young populations are not present in the bulge of M31 (Stephens et al. (2003) or M32 (Davidge et al. 2000). Could some of the youth ascribed to these

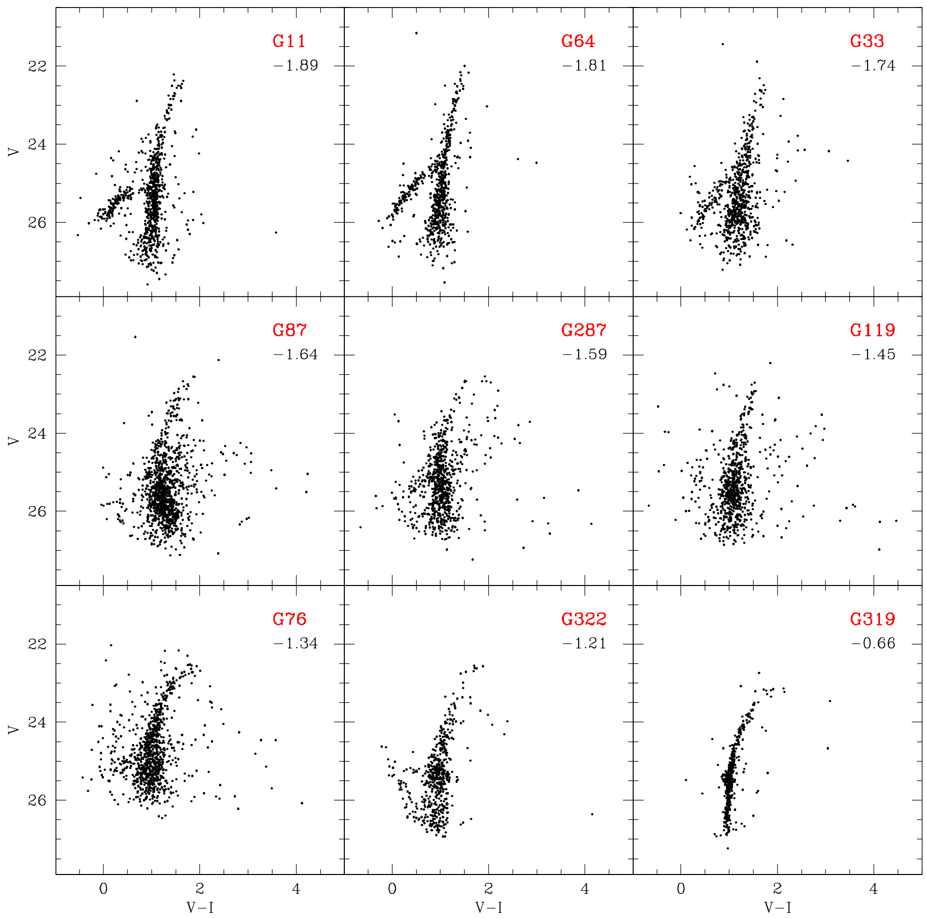

Fig. 1.2. Color-magnitude diagrams for globular clusters in M31 (Rich et al. 2004a) observed using *HST* and WFPC2. Notice that the agreement of horizontal branch morphology with metallicity follows the general trend established by the old globular clusters of the Milky Way halo. Only old stellar populations can produce the observed well-populated blue horizontal branches. The lack of luminous AGB stars and the good correlation between horizontal branch morphology and metallicity are both consistent with this sample being as old as the oldest Milky Way globular clusters. Cluster identifications from Sargent et al. (1977); metallicities from Perrett et al. (2002).

populations be due to the aforementioned blue horizontal branch problem, or related to some other difference in populations?

Turning now to abundances, the M31 cluster abundance distribution is bimodal (as is the case for the Milky Way and other extragalactic cluster populations), with a dominant metal-poor peak at −1.4 dex, and a metal-rich peak at −0.6 dex, which represents about 30% of the overall cluster population (Barmby et al. 2000).

Both metal-rich and metal-poor globular clusters show the clear signature of rotation;

however, the metal-rich clusters have a steeper rotation curve and are also more centrally concentrated (Perrett et al. 2002). These observations would remain consistent with the picture in which the metal-rich clusters are more closely associated with the central bulge, while the metal-poor clusters are connected to the Population II halo.

New developments upset this satisfying picture. As is the case for the Milky Way, there appears to be kinematic subgroups of clusters (Saito & Iye 2000; Perrett et al. 2003; Morrison et al. 2004). This result is not surprising, given that seven dwarf spheroidal galaxies are already identified in the vicinity of M31, and the previously mentioned deep wide-field imaging of the outer halo shows that the galaxy is circled with debris trails extending on scales of tens of kiloparsecs.

But the new analysis of the Perrett et al. velocities would appear to contradict, or at least be inconsistent with, either picture. Morrison et al. (2004) argue that much of the M31 globular cluster population is associated with an extended thin disk. In contrast to the G dwarf problem of the Milky Way, they find the “thin disk” clusters to have as wide an abundance range ($-2 <$ [Fe/H] < 0) as is found anywhere else in M31. If this disk population is real, it poses a serious problem in chemical evolution. How does gas dissipate into a disk so rapidly as to not undergo general enrichment? It is difficult to imagine forming clusters at 1/100 solar abundance after the time scales and dissipation required for the thin disk to form.

1.3.1 The Peculiar Spectra of M31 Globular Clusters

In the 1980s, Faber acquired a very large sample of spectra at Lick observatory, using the then newly commissioned image-dissector scanner (Wampler 1977). It became possible to compare respectable samples of M31 globular clusters with their Galactic counterparts, and with the integrated light of galaxies. Burstein et al. (1984) find that the M31 globular clusters are distinguished spectroscopically from their Milky Way counterparts. Relative to globular clusters in the Milky Way, M31 globular clusters show enhanced CN, and metal-rich M31 globular clusters have stronger $H\beta$ than their Galactic counterparts; findings confirmed by Tripicco (1989). The $H\beta$ enhancement is often attributed to the M31 clusters being a few Gyr younger than the old, Galactic metal-rich clusters, but hot blue horizontal branch stars or blue stragglers may also be responsible.

Subsequent studies in the infrared (Davidge 1990) and in the ultraviolet (Ponder et al. 1998) confirm the CN enhancement. As the ultraviolet light arises mostly from the main sequence while the infrared light is dominated by giants, it becomes difficult to escape the hypothesis that nitrogen enhancement is responsible and caused by a valid difference in abundance. Challenges in both the ultraviolet and infrared observations keep the sample sizes small. Even so, the CN enhancement is confirmed in every case. The metal-rich clusters of the Milky Way bulge have strong CN relative to the bulge field population (Puzia et al. 2002). Chiappini, Romano, & Matteucci (2003) review the evolution of CNO elements in galaxies, and conclude that the evidence favors intermediate-mass stars (4–9 $M_{\odot}$) as being the dominant source of nitrogen, not massive stars. One could argue that the low N/O ratios observed in a ultraviolet-selected sample of starburst galaxies (Contini et al. 2002) support this assertion, as do abundances in damped Lyα systems at high redshift (Lu, Sargent, & Barlow 1998). If the nitrogen excess is intrinsic, one may speculate that M31 globular clusters may have enriched more slowly, or that much of their star formation was extended on Gyr time scales (in sharp contrast to Galactic globular clusters, which have no measurable age dispersion). Perhaps the burst responsible for cluster formation in M31 may have been delayed by ~ 1 Gyr relative to other populations, a difference large enough to affect nucleosynthesis, yet small enough to be undetectable using the AGB, horizontal branch morphology, etc.

The emerging complexity of the M31 halo in both structure and, evidently, age, as well as the claims by Morrison et al. (2004) for a kinematic thin disk of globular clusters, would appear to be contradicted by the well-behaved color-magnitude diagrams of the clusters. On the other hand, the spectroscopic differences between the M31 clusters and those of the Galaxy, and between M31 and the integrated light of elliptical galaxies, argues for some different feature in their chemical evolution. Efforts to measure composition of these systems from high-resolution integrated spectra (Bernstein & McWilliam 2002) would be well worth pursuing.

1.4 The Stellar Halo Population

The perception of the M31 halo has changed fundamentally since the heroic imaging survey of Ibata et al. (2001) and Ferguson et al. (2002). Prior to that work, the dominant view of the halo largely remained that of de Vaucouleurs (1958)—that the halo is largely an extension of the central bulge (we return to this issue in §1.8, however). It would now appear that, instead, M31 is a confirmation of the hierarchical assembly of galaxies, and that the Searle-Zinn approach to considering chemical evolution in the halo is correct. In further support of this scenario is the ultra-deep halo imaging using the Advanced Camera for Surveys (ACS) on board *HST* (Brown et al. 2003), which evidently requires the presence of a 6–11 Gyr old, metal-rich population at 11 kpc (see §1.4.2).

Although the dramatic images of the outer halo of M31 show clearly the possibility of a major merger scenario, much remains to be explained that is simply not consistent with that picture. Interactions and their manifestations are interesting and often spectacular. In the Milky Way there is the Sagittarius dwarf spheroidal galaxy (Ibata, Gilmore, & Irwin 1995) and the tidally disrupted globular cluster globular cluster Palomar 5 (Rockosi et al. 2002). Yet, what fraction of the total halo mass is accounted for by such events? We start by considering the halo abundance distribution, distinctly more metal-rich than the Milky Way halo, yet remarkably uniform over a wide range of galactocentric distance in M31.

The pioneering work of Mould & Kristian (1986) was the first to show that the halo of M31 is composed of a metal-rich stellar population*. Pritchet & van den Bergh (1987) subsequently discovered RR Lyrae stars in a field 11 kpc distant from the nucleus on the SE minor axis; in that location they found also a metal-rich, globular cluster-like population with [Fe/H]≈ -1, and the first secure indication of a predominantly red horizontal branch (confirmed in all subsequent studies). Further work confirmed their early findings (e.g., Pritchet & van den Bergh 1988; Richer, Crabtree, & Pritchet 1990; Holland, Fahlman, & Richer 1996; Rich et al. 1996a; Durrell, Harris, & Pritchet 2001; Bellazzini et al. 2003). Studies of remote major axis fields (Rich et al. 1996b; Ferguson & Johnson 2001) also find a surprisingly metal-rich field population. Sarajedini & van Duyne (2001) argue that the metal-rich stars are related to a thick disk (§1.4.3 discusses the kinematics of these stars). Figure 1.3 shows how striking the high metallicity of the M31 halo is, from the new study of

* Mould & Kristian's imaging of the halo of M31 was undertaken using the prime focus universal extragalactic instrument (PFUEI; Gunn & Westphal 1981) at the 200-inch telescope; the author of this article was present at the observing run.

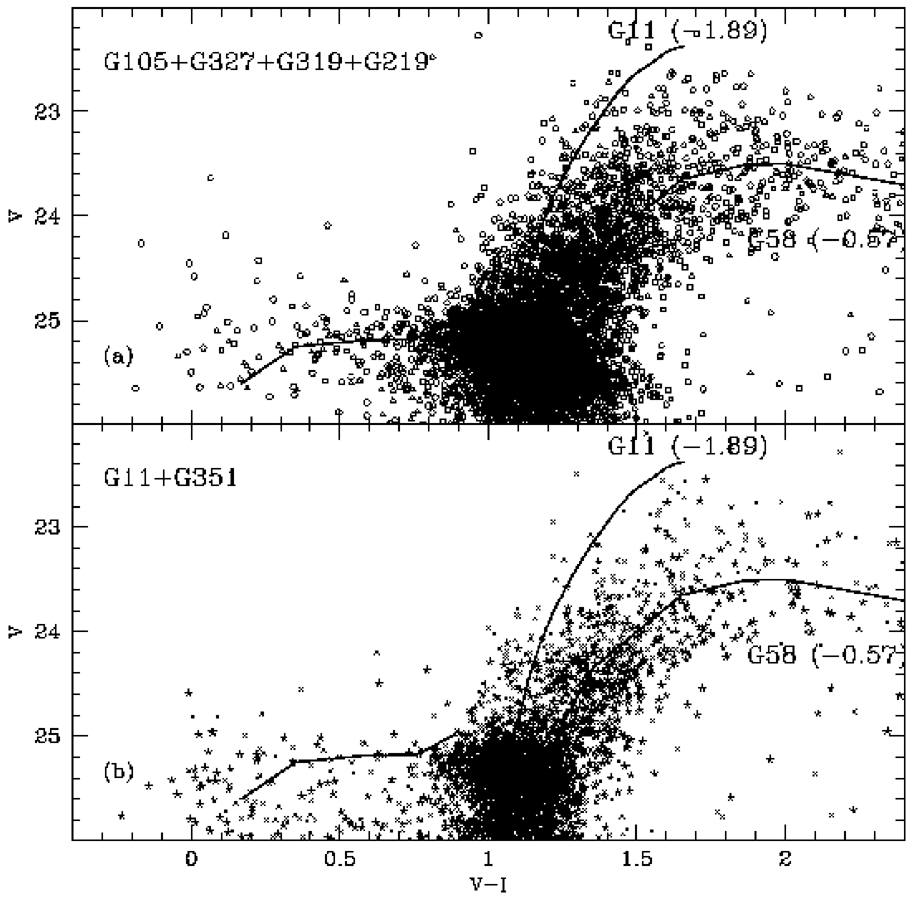

Fig. 1.3. The metal-rich halo of M31 (Bellazzini et al. 2003); photometry from WFC camera frames, where the PC is centered on the globular clusters listed in the two panels. Illustrated are the ridgelines of actual M31 globular clusters with indicated metallicities, as compared to the field halo giant branch. The horizontal branch is that of M68 at the distance of M31. G11 and G351 lie at projected distances > 20 kpc from the M31 nucleus. Halo fields show little change in their RGB color (abundance range) from 5 to 35 kpc from the nucleus. Note that the same analysis performed on NGC 147 (Han et al. 1997) finds no stars redward of the ridgeline defined by 47 Tuc.

Bellazzini et al. (2003). We emphasize here that if the halo field population is younger than the globular clusters, the metallicity must be $0.1-0.3$ dex *higher* than implied in Figure 1.3.

Durrell et al. (2001) find that a halo field 20 kpc distant on the minor axis has a peak

[Fe/H] = –0.8, a result that holds also for a field at 30 kpc (Durrell, Harris, & Pritchet 2004). The abundance distribution (peak at the abundance of 47 Tuc) resembles closely that found by Rich et al. (1996b) in a 34 kpc distant major axis field near G1. Durrell et al. (2001, 2004) determine photometric abundances and assume a globular cluster age population. The abundance distribution fits the standard simple model of chemical evolution, and they argue for a wind-driven chemical evolution model.

How widespread and uniform is the metal-rich population? At first glance, it might be a concern that the stars in the dwarf spheroidal galaxies of Andromeda range from –2 to –1.3, far more metal-poor than is found in the halo. However, (looking ahead to Fig. 1.9) the dwarfs are so distant from the metal-rich halo that they are far more likely to have evolved as self-contained systems, their chemical evolution being dominated by the simple model with metals removed via winds (Hartwick 1976). In contrast to the Milky Way dwarfs, these systems are so distant that it is difficult to consider them as belonging to the inner portions of the halo we address here. However, we can state confidently that accretion of systems similar in metallicity to the Andromeda dwarfs could not account for the bulk of the halo within 35 kpc, as the halo is nearly an order of magnitude too metal-rich. We will consider their chemical evolution in §1.5.

The recent study of Bellazzini et al. (2003) reports on the analysis of WFPC2 imagery of 16 fields ranging from 4.5 to 34 kpc from the nucleus (Fig. 1.4). While the WFPC2 field is tiny, the similarity of filters and exposure times, and clean detection of the red giant branch (RGB) permits us to explore abundance variations (from photometry of the RGB) as a function of position in the M31 halo. The imaging samples a wide range of environments in the galaxy, from fields very clearly superposed on the disk to those adjacent to globular clusters, 30 kpc or more in projected distance (including the G1 field, the most distant at 34 kpc projected distance). The principal result is that there is very little variation in the abundance distribution from field to field, with the exception that fields < 5 kpc from the nucleus reach higher metallicity. It would appear surprising that regardless of whether the field population is superposed on the bright disk and the color-magnitude diagram includes blue stars, or whether the field lies 20 kpc from the nucleus of M31, the color-magnitude diagram is largely the same: a red descending giant branch with a dominant red horizontal branch. However, all fields also have blue horizontal branch stars, which comprise about 15% of the population (from which they infer the fraction of metal-poor stars to be $\sim$15%).

One may ask (referring back to Fig. 1.1) whether any difference can be discerned as a function of environment: do stars in the disk, interaction streams, or undisturbed halo show any differences? Figure 1.5 shows that the disk is both more metal-rich and has a slightly wider abundance distribution than is found in the halo or the disturbed regions. It would appear that the material in these streamers is different from that in the disk of M31, making it less likely that the streams were formed as a consequence of some ancient interaction with the disk.

Metallicities for the field stars have been derived by interpolating between the giant branches of Galactic globular clusters; as mentioned earlier, if the field stars are systematically young, the abundances could be up to 0.3 dex higher. Regardless of whether the metallicities are derived from the Carretta & Gratton (1997) system or are based on the Zinn & West (1984) scale, the distribution has a peak near –0.5 dex with a tail toward the metal-poor end, in the reverse sense of the abundance distribution of the M31 globular cluster population.

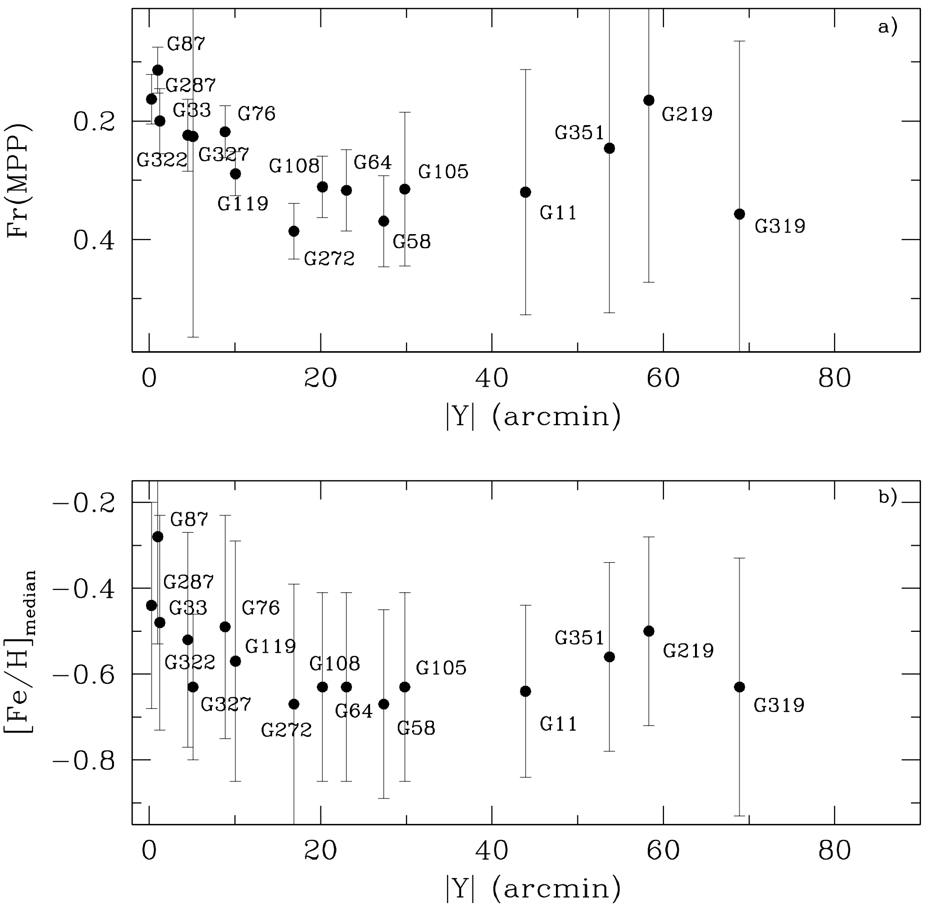

Fig. 1.4. Search for an abundance gradient in the halo of M31 (Bellazzini et al. 2003). The abundances are derived by interpolating between the RGBs of old (12–13 Gyr) Galactic globular clusters, and would be ~ 0.3 dex higher if the population were younger by 4 Gyr. *Upper panel* shows the fraction of stars with [Fe/H]<-0.8 as a function of absolute distance from the major axis in arcmin (note that 10 arcmin = 2.5 kpc). The *lower panel* plots the median abundance. The abundance distributions in M31 generally peak near –0.6 dex and have a tail toward low metallicity. There is little evidence for a gradient in the true halo, outside of 5 kpc, where the disk and inner bulge may contribute significantly. Notice how metal-rich the trend remains; this extends to 34 kpc, the most distant field measured (not shown on these plots), near the globular cluster G1. (Adapted from Bellazzini et al. 2003.)

1.4.1 Spectroscopy in the Halo

Red giant branch tip stars in M31 have $I > 20.5$ mag, faint enough that it is difficult to measure abundances, even with an 8–10 m-class telescope. The best choice for measurement of metallicity is the Ca infrared triplet, although that region of the spectrum suffers from strong night-sky OH lines, which play further havoc with velocity measurements.

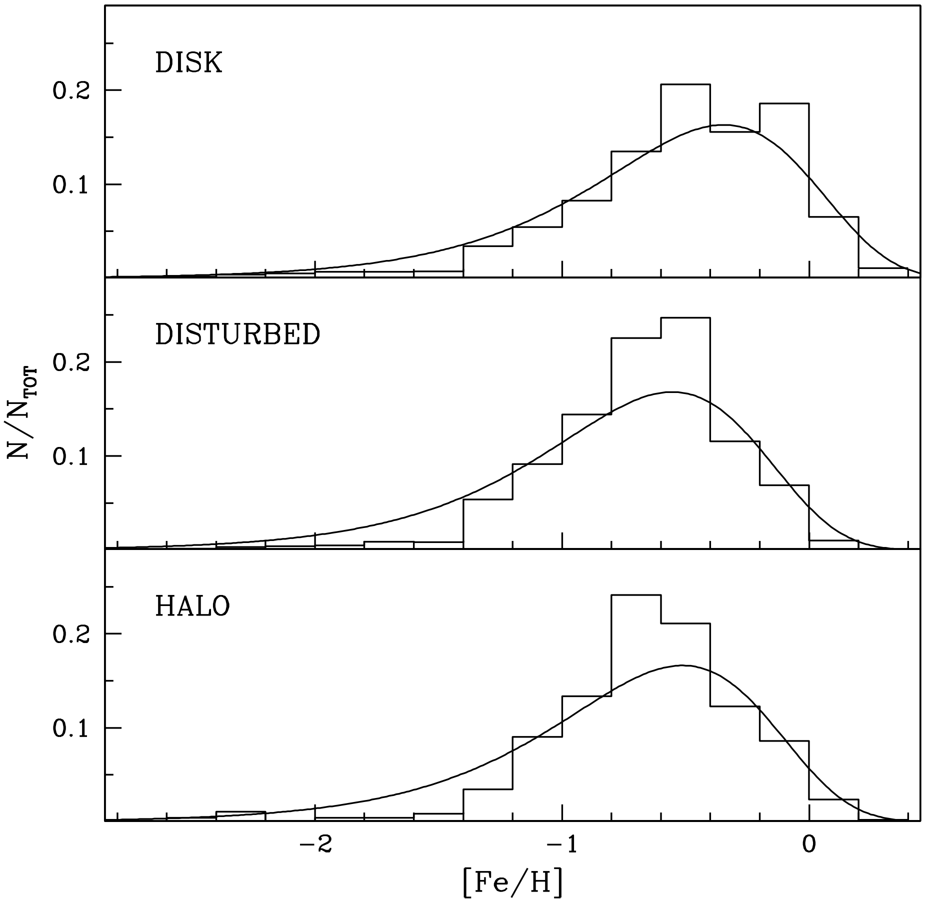

Fig. 1.5. Abundance distributions for giants in M31 fields (derived as in Fig. 1.4). The data are from Bellazzini et al. (2003); plot courtesy of L. Federici. This figure shows that it is unlikely that the interaction streams are comprised of material from the M31 disk. The sample is divided into fields dominated by the disk, interaction regions (see Fig. 1.1 and Ferguson et al. 2002), and the clearly undisturbed outer halo (see Bellazzini et al. 2003 for an illustration and a detailed description). For the disk, the median [Fe/H] = -0.46 ± 0.28 (N = 34091), while for the disturbed regions [Fe/H] = -0.64 ± 0.22 (N = 6220), and for the halo fields [Fe/H] = -0.62 ± 0.23 (N = 420). The solid curve is the fit to the simple model of chemical evolution, with the yield $\log(Z/Z_{\odot})$ as a free parameter, normalized to unity. Fields superposed on the high-surface brightness disk appear to be more metal-rich and follow more closely the simple model than those in the halo or interaction streams, which resemble more closely each other.

Given the 500 km s^{-1} range of stellar velocities in M31, one or more lines of the triplet frequently coincide with night-sky emission; this compromises any spectroscopic abundance measure. Stars near zero radial velocity overlap with the Milky Way halo velocities. Reitzel

& Guhathakurta (2002) report radial velocities and abundances for 99 M31 halo candidates in a field 19 kpc from the nucleus on the SW minor axis. They find that nearly all of the stars in their sample are < -1 dex, whereas in a nearby field adjacent to the globular cluster G319, Bellazzini et al. (2003) find the peak of the (photometric) metallicity distribution to lie at –0.5 dex. If the population in this area is intermediate age, the derived metallicity would increase by 0.2–0.3 dex. As is illustrated in Figure 1.3, the RGB is observed to descend, or decline in luminosity at the RGB tip. Even though the bolometric luminosity of a red giant increases, when the metallicity exceeds ~ -1 dex, molecular blanketing affects the V and, to a lesser extent, the I band. This effect can cause the tip of the RGB to become as faint in V as the red clump, and its widespread presence in the halo manifestly demonstrates that the halo population is metal-rich—or, at least, that TiO bands are present in the red giants, which could also be indicative of α element enhancement. Nonetheless, this observation is difficult to reconcile with the abundance distributions of Reitzel & Guhathakurta (2002), who find few stars more metal-rich than −1 dex. They argue that spectroscopic samples tend to successfully measure velocities and line strengths for only the brightest stars, and that these tip stars are metal-poor (the redder, more metal-rich stars have $V > 23$ mag in the M31 halo).

1.4.2 Age of Remote Fields from Deep *HST* Photometry

Recently, two *HST* imaging campaigns, in which this author is involved, have reached deeper into the halo population than prior studies. Brown et al. (2003) used a 120 *HST* orbit integration to solidly reach the old main sequence turn-off in a field 11 kpc from the nucleus on the SE minor axis (Fig. 1.6). In the first instance, some familiar features of the expected globular cluster-like population are present: the blue horizontal branch, a red clump, and a large turn-off population fainter than the horizontal branch by the canonical 3.5 mag. If the color-magnitude diagram were instead shallow and reached only just past the horizontal branch, it would be reasonable to conclude that the population in question has a component of old, metal-poor stars (based on the extended blue horizontal branch) and likely a fraction of old, metal-rich stars (based on the red clump and RGB). However, in that case we would be misled by the data, and this should be viewed as a cautionary example for those cases where the turn-off cannot be reached. In fact, there is evidently an age range in this population. To explore further the age, we examine the distribution of stars along a diagonal cut that crosses the subgiant branch (Fig. 1.7). It is not possible to fit the number distribution of stars along this cut, nor to achieve a fit to the general appearance of the color-magnitude diagram, using only old (globular cluster age) model populations. In order to avoid uncertainties with color transformations and from other effects, we use the identical filter/detector system to image well-studied Galactic globular clusters spanning a wide range in metallicity. The best fit to the subgiant branch retains a fraction of old (10–13 Gyr), metal-poor stars, but 55% of the population must be 6–11 Gyr old with [Fe/H]> –0.5 and have a continuous star formation history (roughly half of those stars are younger than 8 Gyr).

In a pioneering ground-based study, Pritchet & van den Bergh (1987) find 30 RR Lyraes in a field 9 kpc from the nucleus on the SE minor axis, 2.2 kpc closer than the deep *HST* imaging field discussed earlier. The high specific frequency of RR Lyrae led them to propose that the M31 halo has a well-developed horizontal branch; the specific frequency of RR Lyraes is higher than found in variable-rich Galactic globular clusters. If a majority of the

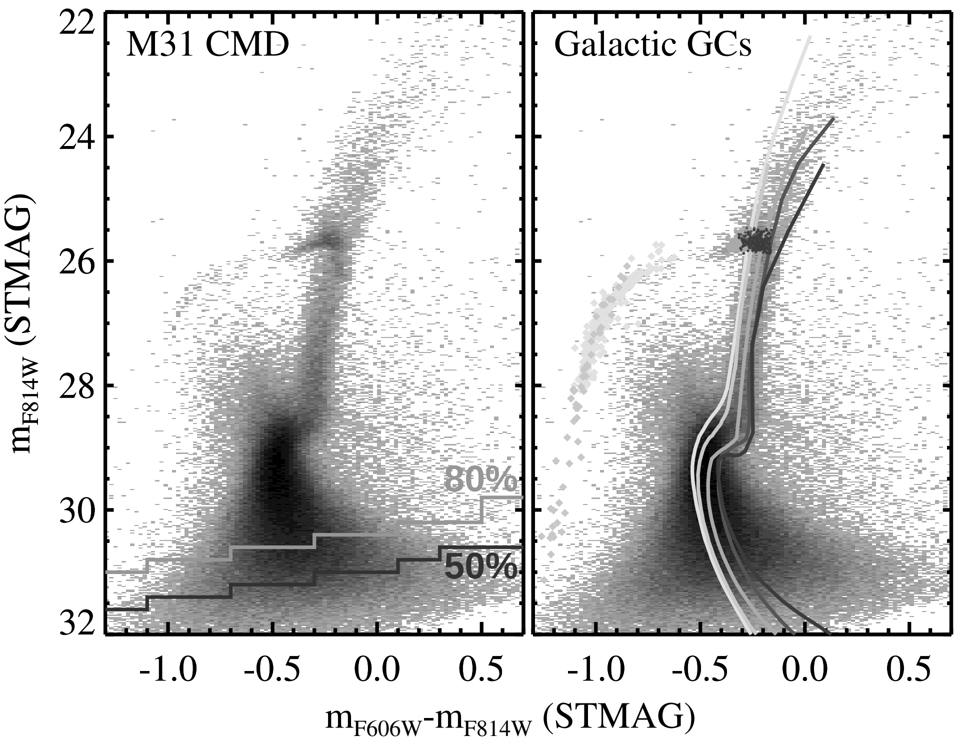

Fig. 1.6. Deep photometry in the M31 halo from the ACS imaging campaign of Brown et al. (2003) presented in the form of a Hess diagram (density plot). *Left panel:* The color-magnitude diagram derived from point-spread function fitting of the ACS images, with completeness limits indicated. Notice the blue horizontal branch (an indicator of great age) and that the old main sequence turn-off is clearly reached. *Right panel:* Ridgelines and horizontal branch loci of Galactic globular clusters, also observed with the same filter and camera as the halo field, are superimposed on the color-magnitude diagram. The clusters range from M92 ([Fe/H] = −2) to NGC 6528 ([Fe/H] = −0.2). The best available determinations in distance modulus and reddening are used to place the cluster loci, except for that of NGC 6528, which is force fit to the red horizontal branch of the M31 field. Note that while the horizontal branch loci of the Galactic clusters coincide with the data, *the subgiant branches of the more metal-rich (redder) clusters lie systematically fainter than the turn-off in the halo field*. (Adapted from Brown et al. 2003.)

more distant field at 11 kpc is composed of a metal-rich, intermediate-age population, then the abundance of RR Lyraes in the remaining old, metal-poor population is extraordinarily large, compared to Galactic globular clusters. The presence of the RR Lyraes requires that a substantial fraction of the population be old (globular cluster age). RR Lyraes are considered to indicate the presence of the oldest stellar populations, and it is difficult to find room for the evidently intermediate-age, metal-rich component.

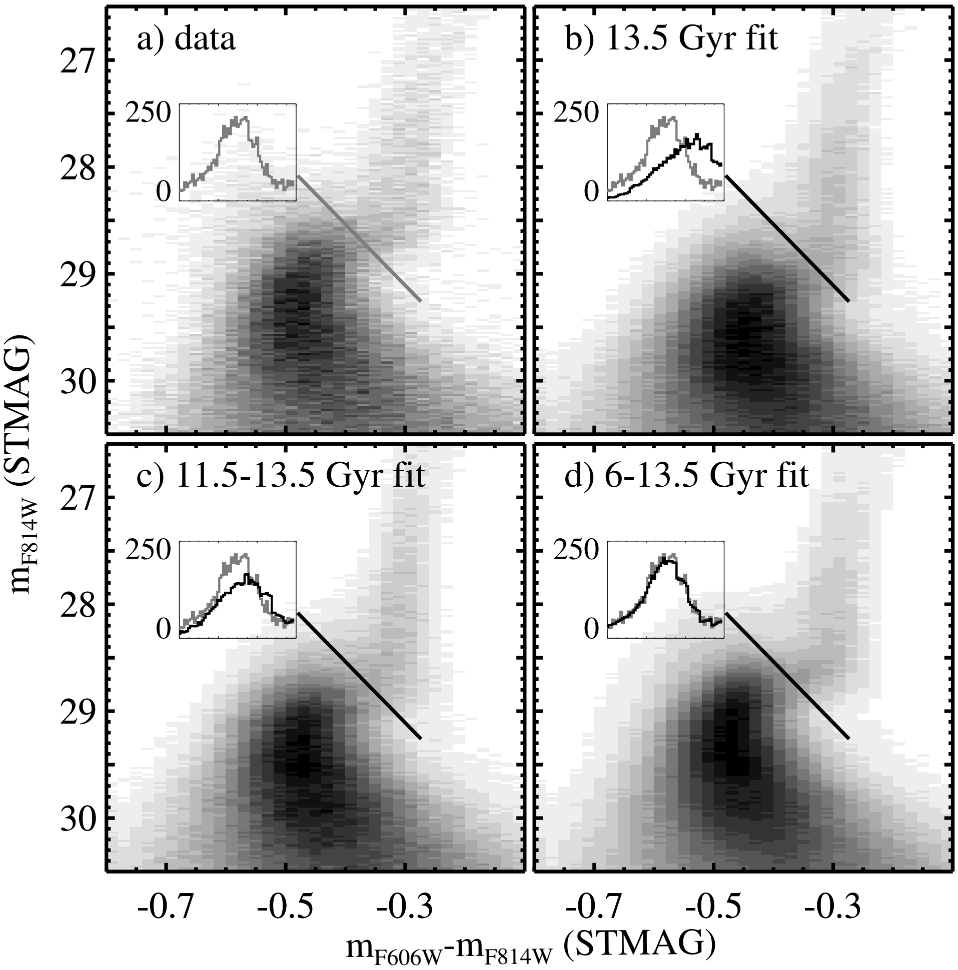

Fig. 1.7. Modeling of the turn-off population in M31; details given in Brown et al. (2003) and Brown (2004). These models are the basis for the argument that the M31 halo must contain a significant population of 6–11 Gyr old, metal-rich stars. The subgiant branch is reasonably complete and has the most straightforward sensitivity to age. (*a*) Histogram resulting from counts of stars along the illustrated line, for the data. (*b*) Fit to the color-magnitude diagram using only 13.5 Gyr stars with a wide range in metallicity. While able to fit the width of the RGB, the subgiant branch fit fails. (*c*) When the age range is broadened to 11.5–13.5 Gyr with a wide permitted abundance range, the fit still fails. (*d*) The fit to the age-sensitive subgiant branch succeeds when the model has 56% of the population with age 6–11 Gyr and –0.5 < [Fe/H] < 0.0, and retains a 30% component of 13 Gyr metal-poor stars that fit the blue horizontal branch. (Adapted from Brown et al. 2003.)

1.4.3 A Remote Field 34 kpc Distant on the Major Axis

Although reaching only a fraction as deep as the halo field, a second deep field (and the second deepest analyzed to date) lies near the luminous globular cluster G1. Also nearby (Fig. 1.1) is a distinct plume in the irregular halo distribution, suggested by Ferguson

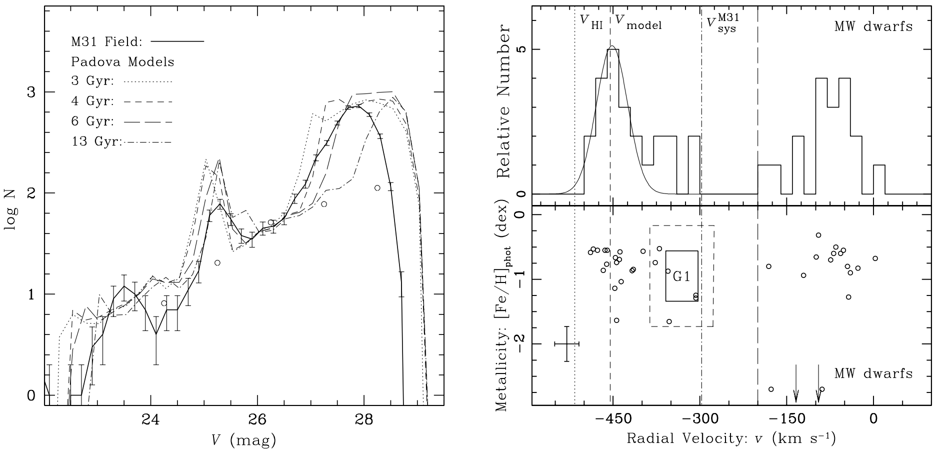

Fig. 1.8. *Left:* Deep luminosity function in the field of the M31 globular cluster G1, 34 kpc from the nucleus on the SW major axis (Rich et al. 2004b). Model luminosity functions constructed from the Padova isochrones show that a pure old globular cluster age population fails to fit the counts. The Padova luminosity functions include a completeness correction. The RGB slope indicates the field is metal-rich, at ~ -0.7 dex. *Right:* Radial velocities and photometric abundances for K giants in the same field near G1 (Reitzel et al. 2004). Half the stars are consistent with foreground Milky Way membership, while a handful are plausibly at the velocity of G1. The majority of stars lie near the velocity that the disk of M31 would have at that location, as inferred from the global velocity field of neutral hydrogen in M31. The velocity of the nearest detected neutral hydrogen, some 2 kpc distant, is indicated in the upper panel.

et al. (2002) as possibly corresponding to the remnants of a low-luminosity galaxy that had G1 as its nucleus. Both Rich et al. (1996b) and Meylan et al. (2001) suggest that this massive ($\sim 10^7 M_\odot$) cluster could have once been the nucleus of a dwarf elliptical galaxy. Support for this idea gained momentum both from the abundance spread found by both of the above studies, and by the strong hint of halo structure near the position of G1. Finally, the kinematic detection of a $10^4 M_\odot$ black hole in the core of G1 (Gebhardt, Rich, & Ho 2002) might appear most consistent with a galactic nucleus classification.

Fortunately, we have Keck spectroscopy in the field, and we are able to explore both the kinematics of the field as well as the deep photometry. Figure 1.8 shows our deep luminosity function in the vicinity of G1. Although the stellar population appears to be old in this vicinity, it is clearly not as old as a globular cluster age population. The presence of carbon stars some 32 kpc distant on the major axis (Brewer, Richer, & Crabtree 1995) would confirm the idea that the population in this field has a substantial disk component.

Keck radial velocities near G1 (Fig. 1.8) are a surprise. The majority of stars appear offset from the G1 radial velocity by > 100 km s^{-1}. We find that most of the stars in the field have velocities that would be consistent with the rotation of the disk, rather than with either the velocity of G1 or the systemic velocity of M31. While our velocities do not *prove* that the stars follow the kinematics of the disk, they do show that very few stars in this region are associated with G1. The star counts of Meylan et al. (2001) follow a King profile to a distance of 200″ from the center, but no hint of a deviation from a King profile (as might be expected if there is an associated dwarf spheroidal galaxy) is seen. It now appears as if the field stars have more to do with the fossil disk of M31 than with any remnant dwarf galaxy, or even the halo.

1.5 The Distant Companions

M31 has a growing retinue of companions, which include NGC 185, NGC 147, and the Andromeda dwarf spheroidal galaxies; Figure 1.9 shows that they all lie well outside even the outer portions of the surveyed stellar halo. The Andromeda dwarfs are significantly more metal-poor than the halo (Fig. 1.10), as determined from their blue RGBs, blue horizontal branches, and RR Lyrae stars (e.g., Mould & Kristian 1990; Da Costa, Armandroff, & Caldwell 2002; Pritzl et al. 2002). Spectroscopy of giants in And II (Côtè, Oke, & Cohen 1999) finds [Fe/H] = -1.47 ± 0.19 and a 0.35 dex spread. Even NGC 147, which is more metal-rich than the Andromeda dwarfs (Han et al. 1997), has a RGB that is clearly bounded on the red side by the locus of 47 Tuc, at -0.7 dex. The globular cluster systems of NGC 147, 185, and 205 are also metal-poor (Da Costa & Mould 1988). Their abundances range from -2 to -1.3 dex and, with the exception of Hubble V in NGC 205 (for which star formation is documented), the spectra are consistent with the clusters all being as old as their Galactic counterparts. The metallicity-luminosity and metallicity-surface brightness relationships for dwarf spheroidal galaxies have been considered in various papers. The plots given by Saviane, Held, & Piotto (1996) show that the Andromeda dwarfs, NGC 147, 185, and 205 fall on the same relationship as defined by Galactic dwarf spheroidal galaxies. The general trend and relatively low scatter suggest that in these systems the mean metallicity is regulated by the flow of metal-enriched winds out of the protogalaxy's potential well. More massive galaxies reach higher metallicities by retaining more gas. The chemical evolution for these galaxies would be described by Pagel & Patchett (1975), Hartwick (1976), and Mould (1984). The abundance distribution has the same shape as the simple model (broad abundance range), but the mean is lower because the wind-driven loss of metals reduces the effective yield. Dekel & Woo (2003) present a more current consideration of these issues in dwarf galaxies and are able to reproduce the observed metallicity-luminosity-surface brightness correlations as the result of supernova-driven winds bound by a dark matter potential, with metallicity regulated by the loss of gas.

The star formation history of the companions appears to be more complicated than that of the globular clusters. While it has been clearly demonstrated (e.g., NGC 205; Lee 1996) that the populations of the M31 companions have age ranges, RR Lyrae stars and blue horizontal branches have been found in every Andromeda dwarf for which the appropriate data have been taken (see Pritzl et al. 2002), as well as in NGC 147 (Saha, Hoessel, & Mossman 1990), NGC 185 (Saha & Hoessel 1990), and NGC 205 (Saha, Hoessel, & Krist 1992). The presence of RR Lyrae stars in these systems requires that they harbor at least a significant fraction of old and metal-poor stars, though Da Costa et al. (2002) suggest that the fraction of intermediate-age and young stars in these galaxies increases with distance from M31. Blitz & Robishaw (2000) found neutral hydrogen associated with And III and And V. Thilker et al. (2004; see Fig. 1.11) found numerous high-velocity clouds of neutral hydrogen in the vicinity of M31, which could provide fuel for ongoing star formation. The infall of gas has doubtless been important in chemical evolution and the building of the disk (Blitz et al. 1999).

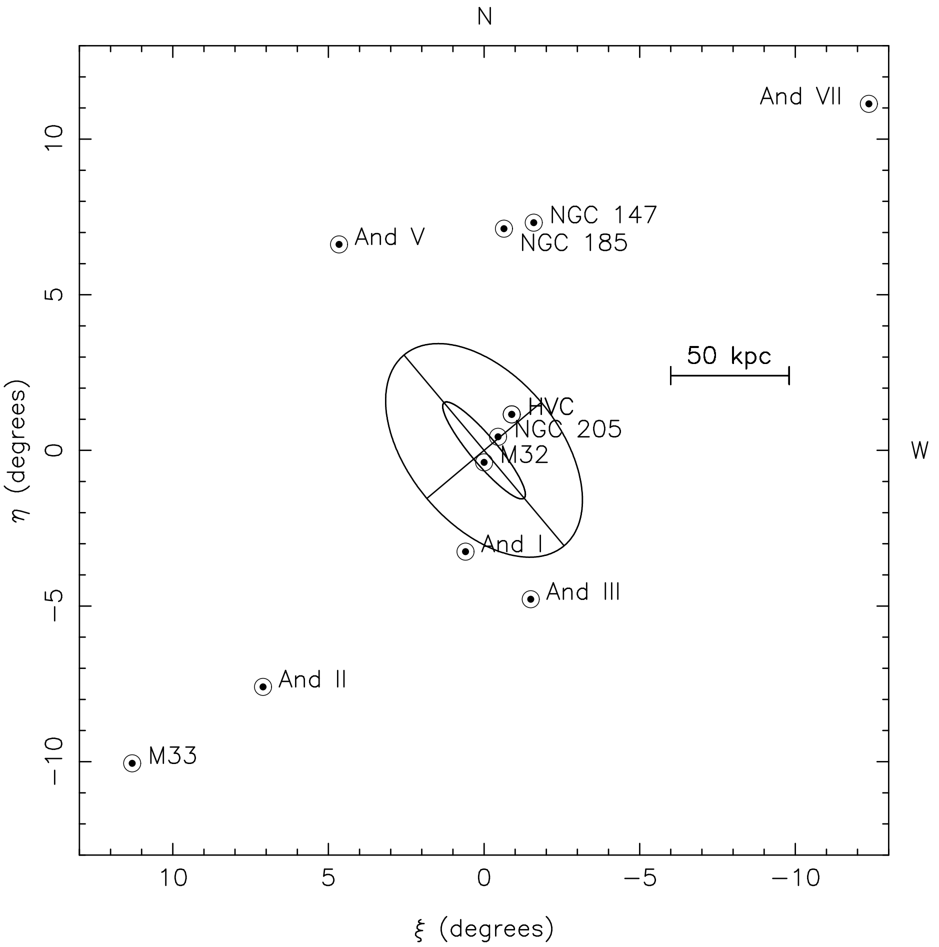

Fig. 1.9. Projected distribution of the satellite companions and Local Group galaxies nearest to M31 (from Ferguson et al. 2002). The figure also shows a massive cloud of neutral hydrogen (labeled HVC) detected by Davies (1975). The ellipse circumscribing M31 and the limit of the optical disk is the outer bound of the Ferguson et al. (2002) survey; the elliptical distribution of halo material lies within that bound. The great distance of the companions of M31 suggests why these systems appear to have evolved following wind-driven chemical evolution with some modification by gas infall (Blitz & Robishaw 2000 find H I in And III and And V). The M31 halo population remains metal-rich at 34 kpc on the major axis (Rich et al. 1996b) and to 30 kpc on the minor axis (Durrell et al. 2004), where both the mean metallicity near [Fe/H] = −0.7 and the dispersion are confirmed.

Finally, there is the case of M32, a galaxy that has been suggested to have been tidally stripped from a formerly more massive system (Faber 1973; Choi, Guhathakurta, & Johnston 2002) and for which there is evidence of tidal tails. The stellar population in M32 is metal-rich; the RGB descends just as it does for the M31 metal-rich halo population, and the best-fit isochrone is at roughly −0.4 dex (Grillmair et al. 1996), while Trager et al. (2000)

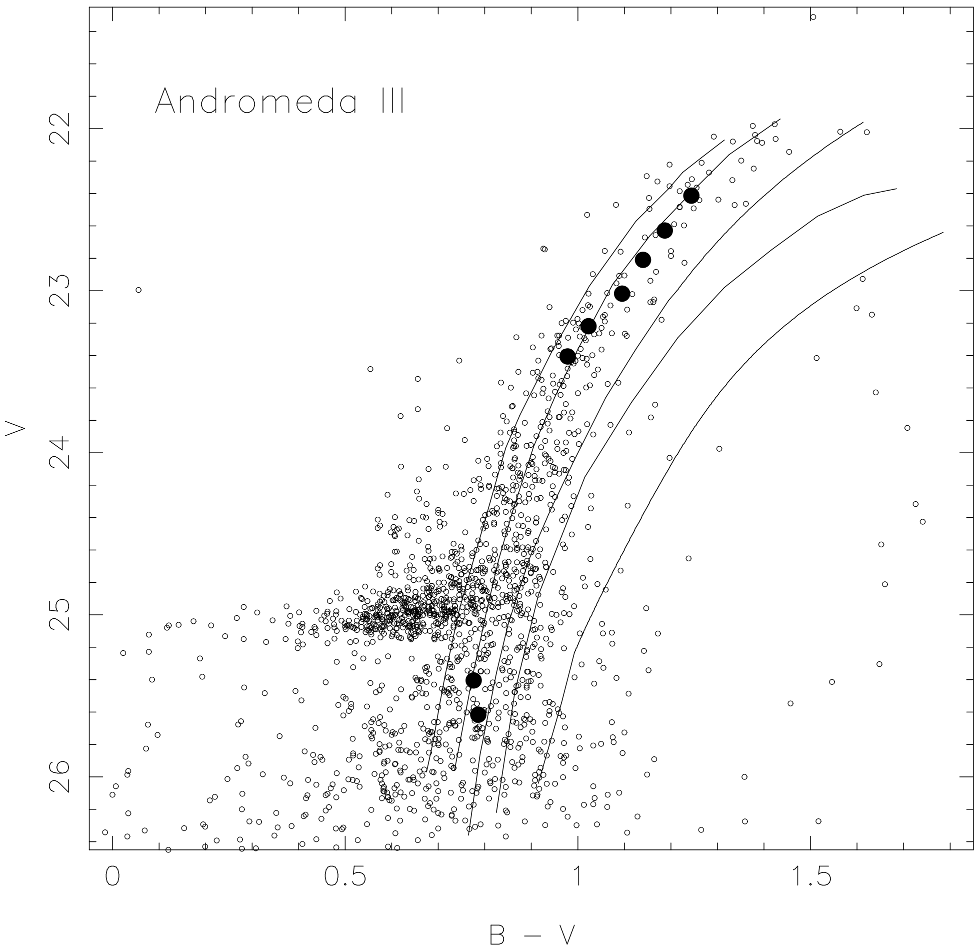

Fig. 1.10. Color-magnitude diagram of And III (Da Costa et al. 2002), which shows the metal-poor RGB and well-populated horizontal branch that typifies the dwarf spheroidal galaxies of M31. Variable stars are omitted in this plot. Empirical giant branches are from M68 ([Fe/H] = –2.09), M55 ([Fe/H] = –1.82), NGC 6752([Fe/H] = –1.54), NGC 362([Fe/H] = –1.28), and 47 Tuc ([Fe/H] = –0.71). The ridgeline of the typical M31 halo field is on average more metal-rich than that of 47 Tuc. The somewhat red distribution of the horizontal branch likely reflects that a significant fraction of the population is $\sim$ 10 Gyr old (i.e. intermediate age). Notice the wide spread in the RGB color, which is not typical for globular clusters.

and Beasley et al. (2004) find solar [Fe/H] and [α/Fe]. Early studies found bright AGB stars in the infrared (Elston & Silva 1992; Freedman 1992). However, the infrared luminosity function of Davidge et al. (2000) is not brighter than that in the M31 bulge (Stephens et al. 2003); yet, both the Trager and Beasley studies, mentioned above, fit M32 at 3 Gyr, significantly younger than M31. Discovery of RR Lyrae stars in M32 would confirm the presence of at least an underlying old population, and deep photometry might quantify the age spread; *HST* observations aimed at these programs have been obtained or are in progress.

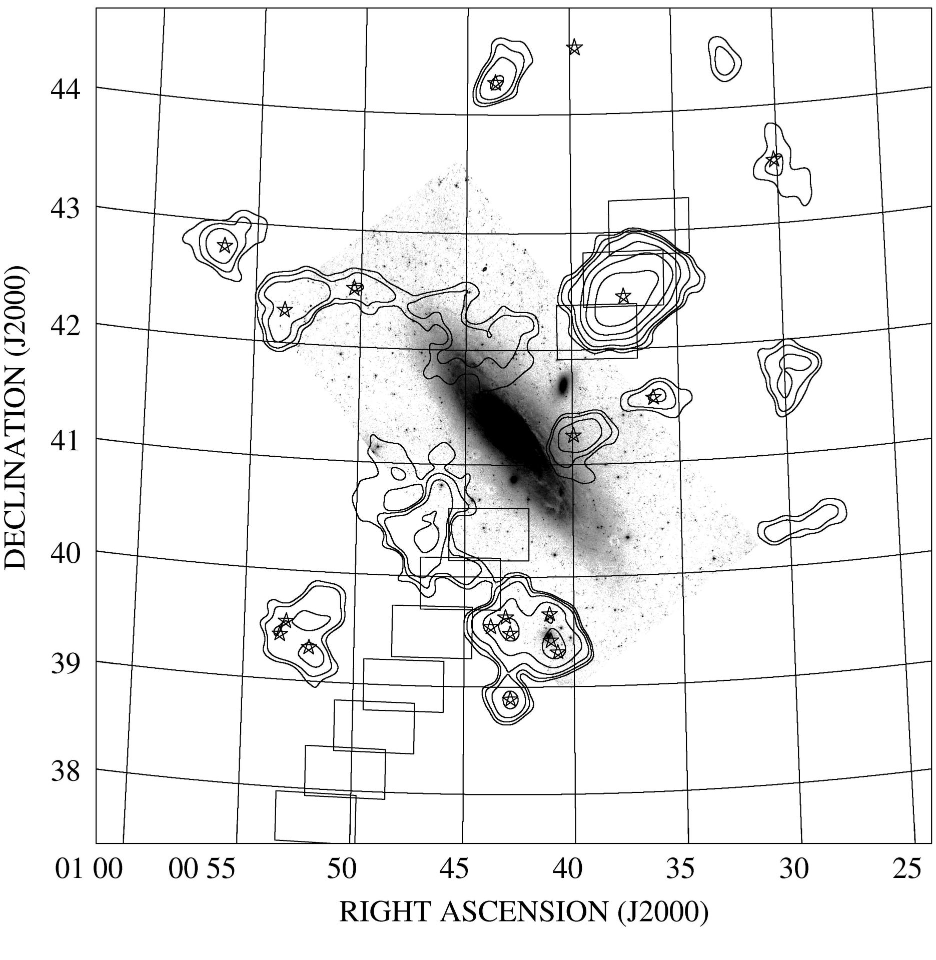

Fig. 1.11. High-velocity clouds of neutral hydrogen near M31, from the new imaging survey of Thilker et al. (2004). Emission from the M31 disk and NGC 205 has been masked and is not shown. A star symbol marks the position of each discrete cloud, and the series of rectangles shows the location of the stream (Ferguson et al. 2002). Contours are at 0.5, 1, 2, 10, and $20\times10^{18}\,\mathrm{cm}^{-2}$. The large amounts of neutral hydrogen in the vicinity of M31 may have fueled the formation of intermediate-age populations that are detected in the outermost of the Andromeda dwarfs (even though their locations are well outside the boundaries of this plot).

Applied to the case of M31, it would appear that the halo field population within 20 kpc is not dominated by the debris of dwarf galaxies, unless they are the debris of a galaxy with $M_V < -18$ mag. Supporters of a "spaghetti" halo scenario for M31 might be disappointed, unless that spaghetti were to come from one plate, perhaps M32 or a galaxy as luminous as it. The halo of the Milky Way also does not appear to consist mostly of stars with chemistry resembling present-day dwarf spheroidal galaxies, as Shetrone, Côté, & Sargent (2001) and Tolstoy et al. (2003) find that stars in the dwarf spheroidal galaxies are depressed relative to the halo in α elements.

1.6 The Bulge

"However, Morgan's spectra, taken at McDonald Observatory with a quartz spectrograph, showed that the cyanogen bands in the ultraviolet are very strong in the integrated spectrum—quite as strong as in normal giants" (Baade 1963; p. 254).

Morgan's early spectroscopy linked the nucleus of M31 to the giant ellipticals and gave strong indication of both large age and high metallicity. The pioneering photometry (*U* through *K*) of Sandage, Becklin, & Neugebauer (1969) showed the nuclear region to be as red as the most luminous Virgo ellipticals. Numerous spectroscopic studies followed and confirmed these fundamental results. Bica, Alloin, & Schmidt (1990) used a library of star clusters and modern CCD spectroscopy to argue that the nucleus and bulge are old and metal-rich, and that an abundance spread must be present (they also found a 10%–20% intermediate-age component). Davidge (1997) undertook a comprehensive spectroscopic assay of the bulge, finding strong CN lines (as in the M31 clusters) and spectral indices that place the bulge and clusters of M31 apart from the Milky Way globular clusters. Worthey, Faber, & González (1992) found a high Mg_2 Lick index, comparable with that in giant ellipticals. As is also the case for the giant elliptical population, the M31 nucleus has strong Mg_2 relative to iron, although Davidge (1997) argued that this declines toward the nucleus. (It is noteworthy that in the same plot of iron vs. Mg_2, M32 lies below the giant elliptical population on the solar composition line.) The population synthesis of Lick indices by Trager et al. (2000) gives [Fe/H] = 0.21 ± 0.05 and [E/H] = 0.19 ± 0.02, where [E/H] reflects elements produced in massive-star supernovae. Beasley et al. (2004) used new Keck/LRIS spectra and fit their indices to the Thomas et al. (2003) models to find the same α enhancement but higher [Fe/H] = 0.5 ± 0.1. Both studies, however, find a young age for the M31 bulge (6–7 Gyr), which is not consistent with the AGB properties described below. The photometry of red giants ~ 1 kpc from the nucleus is consistent with solar abundance with a dispersion (like the halo). The range likely reflects the simple model of chemical evolution, as is the case for the Milky Way bulge (Rich 1990).

Beasley (2004) models the abundance of the M31 and Galactic bulges using the Lick indices for Milky Way bulge fields from Puzia et al. (2002) and his own measurements in M31. The total metallicity [Z/H] = -0.10 ± 0.2 for the Galactic bulge, and [Z/H] = 0.48 ± 0.1 for the M31 bulge. The Type II supernova "α" enhancement is 0.3 ± 0.3 for the Galactic bulge, and 0.2 ± 0.1 for the Milky Way bulge. The mild α enhancement in the Milky Way bulge is seen by Maraston et al. (2003) and is found in the spectra of individual stars (McWilliam & Rich 1994).

For an intense starburst and rapid enrichment, chemical evolution models have long predicted enhanced α elements from the Type II supernova contribution (Matteucci, Donatella, & Molaro 1999). It is the intensity, not the absolute timing, of the starburst that controls the composition (i.e., the composition does not rule out an intermediate-age burst).

In the late 1980s the author noted that the brightest giants in the Galactic bulge are both luminous (reaching $M_K < -8$ mag) and rare (their lifetimes are $\sim 10^5$ yr). It occurred to the author that it might be feasible to image individual AGB stars in the bulge of M31 using ground-based infrared arrays. Rich et al. (1989) obtained optical spectra of individual, resolved red giants in M31, showing that they are ordinary red giants (not carbon stars). Rich & Mould (1991) subsequently imaged a field in the M31 bulge roughly 500 pc from the nucleus, comparable to the distance of the well-studied Baade's Window field of the Galactic bulge from the Galactic nucleus. These observations created quite a stir at the time. Rich & Mould (1991) claimed that they might have detected more bright giants than are present in the Galactic bulge from the Frogel & Whitford (1987) luminosity function. Renzini (1998) simulated the tendency for crowding to produce spurious stars at the bright end. Higher-resolution imaging in the form of adaptive optics shows that M32 (Davidge et al. 2000) and the bulge of M31 (Davidge 2001) have AGB luminosity functions agreeing with that of the Milky Way bulge, hence consistent with an old age. The comprehensive *HST*/NICMOS study of the M31 bulge by Stephens et al. (2003) proves this convincingly. Their imaging finds that the RGB in M31 extends to $M_{\rm bol} = -5$ mag, but that the shape of its luminosity function is similar to the Frogel & Whitford bulge luminosity function. However, Stephens et al. (2003) find no variation in the bright end of the luminosity function, regardless of whether disk- or bulge-dominated fields are considered. Frogel & Elias (1988) note that long-period variables in globular clusters reach $M_{\rm bol} < -4.5$ mag, brighter than the He core flash limit. Guarnieri et al. (1998) find an AGB star at $M_{\rm bol} = -5$ mag (long thought to be attained only by intermediate-age stars) in the old, metal-rich cluster NGC 6553. Present observations in the M31 bulge can only rule out a significant population of few Gyr old stars. Note that Rejkuba et al. (2004) find the brightest AGB stars in the halo of NGC 5128 to be 0.5 mag brighter than in the Milky Way bulge. The period distribution of the Miras in NGC 5128 is weighted more toward long periods ($>$ 500 days) than in the Galactic bulge; even at high metallicity, there comes a point when intermediate age has an effect on the AGB. It is therefore reasonable to conclude that the similarity of the M31 bulge AGB luminosity function with that of the Milky Way bulge strongly argues for M31 being old, like the Milky Way bulge.

1.6.1 Abundance Spread and Gradient

Present observations are all consistent with the bulge of M31 having a population of *metal-rich* stars. The *HST*/WFPC2 imaging of Jablonka et al. (1999) resolves the red giants in three pure bulge fields 0.8 to 1.6 kpc from the nucleus [also finding no abundance or population gradient in that region, somewhat in contradiction to the $\Delta[\mathrm{Fe/H}]/\Delta \log r = -0.5$ gradient from Davidge's (1997) spectra]. Figure 2 of Jablonka et al. shows a wide RGB similar to halo fields but extended toward the metal-rich side. However, the blue envelope is steep, as is seen in metal-poor globular clusters, suggesting that the metal-poor side is represented. Planetary nebulae near the bulge are metal-poor (Jacoby & Ciardullo 1999) but generally lie beyond 1 kpc. A new abundance distribution (derived from $V-K$ colors) for the Milky Way bulge (Zoccali et al. 2003) has fewer metal-poor stars than predicted by the simple model of chemical evolution. However, we have known since the work of Baade (1951) that the bulge has RR Lyrae stars, and hence at least some old, metal-poor population.

In the case of M31, it would be helpful to have higher spatial resolution optical photometry (optical colors are more sensitive to metals so the presence of metal-poor stars is more easily discerned) or spectroscopy of individual giants. The new Keck infrared spectrograph OSIRIS (Larkin et al. 2003), to be commissioned in 2004, might enable such studies. If the abundance range does lack the metal-poor tail, then the simple model cannot fit the abundance distribution. One might suspect that the first generation of long-lived stars in the protobulge was pre-enriched, perhaps by an earlier generation formed in a starburst so violent that low-mass stars were not formed.

1.7 The Halo of M31 and Extragalactic Halos

As the halo populations of more distant galaxies have come under study, it has become clearer that massive galaxies generally appear to have metal-rich halos. Just as is found in M31, the RGB is metal-rich in the halo of NGC 5128 (Harris, Harris, & Poole 1999), but there is more likelihood of an age range (Rejkuba et al. 2004). Evidence for a merger in NGC 5128 is not surprising, given the presence of many merger signatures in this system. In the case of M31, the presence of a significant intermediate-age population in the halo is more difficult to accept, even in the light of the apparent merger signatures in the Ferguson et al. (2002) study. Is the metallicity of halos controlled by the mass of the most significant merger, the depth of the potential well, or by the star formation history?

In order to address this question, the author has collaborated on an *HST* program to image fields in the halos of nearby spiral galaxies that are close to edge-on, thus having a geometry that permits study of the halo (GO-9086; PI H. Ferguson). We have imaged halo fields of galaxies covering a range in luminosity and have derived photometric metallicities for the stars by interpolating between empirical RGBs of Galactic globular clusters. This method has the potential to be in error if the populations are intermediate age, but the largest offset would be +0.3 dex, not large enough to affect the trend.

Figure 1.12 shows our trend of halo metallicity as a function of parent galaxy luminosity. It is interesting that bulges of galaxies show a similar relationship (Jablonka, Martin, & Arimoto 1996). It is difficult to imagine how such a relationship could result if halos are built, in general, out of the mergers of less luminous systems. Rather, the presence of such a trend suggests that the global potential well of the galaxy regulates the outflow of metals, which might be driven by a starburst (originally the chemical evolution model of Hartwick 1976). It is tempting to find support for such a scenario as well in the metal-rich intergalactic medium seen in X-ray studies of clusters of galaxies.

Perhaps wind regulation of the metallicity via the depth of the potential well is in fact the dominant physical mechanism at work. In that case, the *timing* of the starburst does not enter, only its intensity and duration. If further investigation finds punctuated starburst events in the halo, we could expect these events to be accompanied by α enhancement and winds. However, an intense starburst is required to establish a wind; if the star formation in the halo was continuous from 13 to 6 Gyr ago, that would be a problem for the wind scenario. In that case, one also expects the metal-rich stars to have a solar composition (enough time for Type Ia supernovae to contribute iron).

In seeking to explain the high metallicity of the bulge and halo relative to the Milky Way, one might hope to appeal to the greater mass of M31. But that argument would be wrong. If anything, the Milky Way is the more massive. Evans & Wilkinson (2000) find $12.3^{+18}_{-6} \times 10^{11} M_\odot$ for M31 and $19^{+36}_{-17} \times 10^{11} M_\odot$ for the Milky Way. In units of $10^{11} M_\odot$, Evans et al. (2000) find 7–10, while Côtè et al. (2000b) find a median mass of 7.9 ± 0.5. Gottesman, Hunter, & Boonyasait (2002) argue that the upper bound on the mass of M31 must be $6 \times 10^{11} M_\odot$, within a 350 kpc radius, less than that of the Milky Way. If we cannot appeal to the depth of the potential well to explain the difference, Hodge (1992) compares the total luminosity of M31 ($M_B = -21.1 \pm 0.4$ mag) with that of the Milky Way

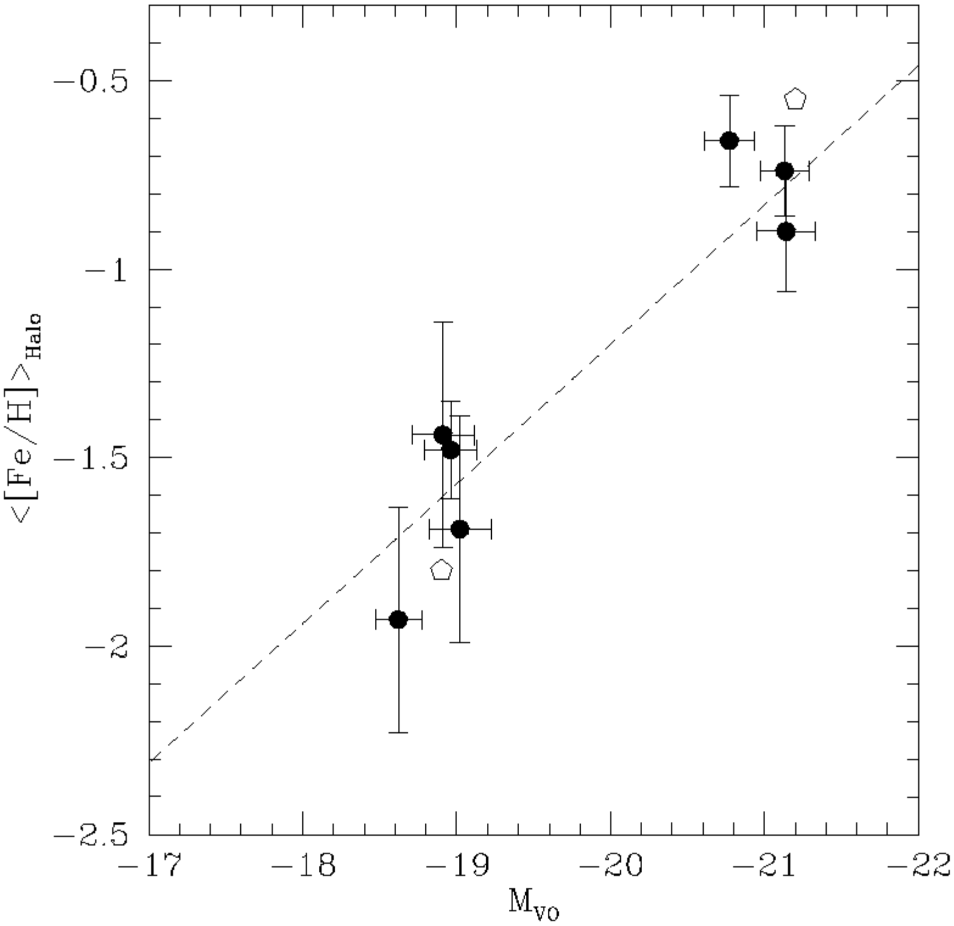

Fig. 1.12. Mean metallicity of the halo population at approximately 10 kpc projected distance from the nucleus, as a function of total luminosity of the parent galaxy. This plot is derived from measurements using WFPC2 onboard *HST* (see text; Ferguson et al. 2004). The pentagons indicate M33 (low metallicity) and M31, respectively. The trend suggests the presence of a luminosity-metallicity relationship for halo populations, as is found also in elliptical galaxies and bulges. The trend for more luminous systems to be more metal-rich would be consistent with the potential well regulating the loss of metals via enriched winds. A scenario in which halos are built from the merger of low-mass galaxies would not successfully produce such a relationship.

($M_B = -20.5 \pm 0.5$ mag). Perhaps it is the mass in baryons, which controls the intensity of the starburst, that drives the chemical evolution and may explain partially the high metallicity in the distant halo. The large study of Kauffmann et al. (2003) from the SDSS database shows that galaxies with stellar mass in excess of $3 \times 10^{10} M_\odot$ have old, metal-rich populations that are likely to have been in place at early times. The picture of the early wind enriching the

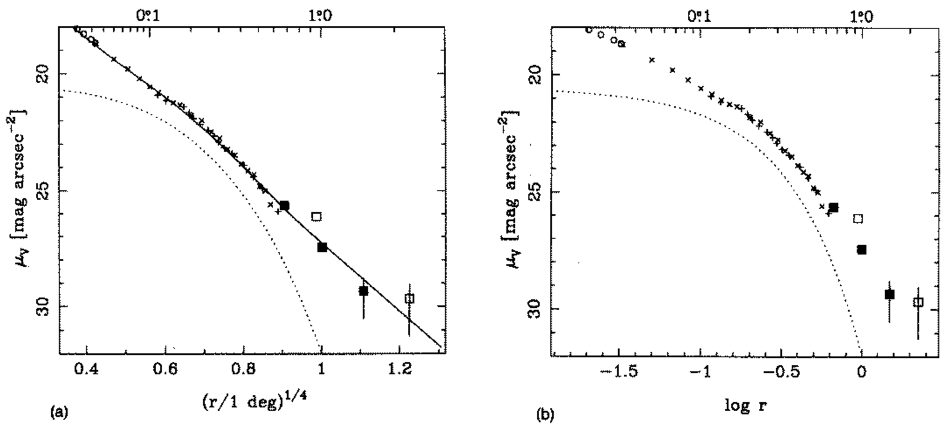

Fig. 1.13. The halo of M31 has a regular surface brightness profile on a scale of 10 kpc (0.75°), even if there are clear signs of a past merger (Pritchet & van den Bergh 1994). We also know that the abundance distribution from 20 to 30 kpc does not change (Bellazzini et al. 2003; Durrell et al. 2004). The *left panel* shows the radial profile versus $r^{1/4}$, hinting that the halo may be an extension of the bulge/spheroid. The *right panel* shows the profile vs. $\log r$. Plotted symbols are from the following sources: circles, Kent (1983); crosses, Walterbos & Kennicutt (1987); open and solid squares, Pritchet & van den Bergh (1994). The open squares are off-minor axis points, and provided the first hint that the halo is flattened. The dotted line shows the disk model of Walterbos & Kennicutt (1988), while the solid line is the sum of their disk plus spheroid model.

M31 halo with metals is attractive, except for the Brown et al. (2004) finding of the age range. A consistent picture of chemical evolution remains beyond reach.

Figure 1.13 reminds us that earlier studies (Pritchet & van den Bergh 1994) find regularity on scales of 10–20 kpc in the surface brightness distribution. As we noted earlier, Durrell et al. (2001, 2004) find no change in the abundance distribution from 20–30 kpc. Are the giant stream and apparent flattened structure in Figure 1.1 (Ferguson et al. 2002) unduly focusing our attention to the merger picture as opposed to *in situ* starbursts? One might speculate that the structure formed from the metal-enriched gas that was expelled on Mpc scales from the galaxy by the bulge-forming primordial starburst (Adelberger et al. 2003) and then cooled (and probably self-enriched), forming the flattened halo. Large programs aimed at measuring the stellar dynamics of the M31 halo structures could lead toward some answers.

1.8 Summary

Since the days of Baade's intensive study of M31 from Mt. Wilson, the galaxy that provided the template for the stellar populations concept has proven to be incredibly complicated. The chemical evolution of the distant satellites of M31 appears to have been regulated by starburst-driven winds confined by a potential well. The globular clusters of M31 resemble in some broad way the system of the Milky Way, as opposed to that of, say, the Magellanic Clouds. The mean abundance of the M31 halo is broadly where one expects it should be for a galaxy of the luminosity of M31.

There are signs of great complexity in M31, however. A large fraction of the globular clusters may in fact be divided into kinematic subgroups, one of which may coincide with the thin disk. Although the color-magnitude diagrams of M31 globular clusters behave as expected, they evidently have a puzzling excess of nitrogen and are otherwise distinct in many line-strength trends from the well-studied Milky Way globular clusters. The halo has been revealed to have clear indications of interactions and mergers. Direct measurement of the old main sequence turn-off in a field 11 kpc from the nucleus, where one would expect a pure globular cluster-age population, instead can be understood only if half the stars are metal-rich and range in age from 6–11 Gyr.

In this modern day, the study of M31 once again has an important lesson to teach us, which is a caution against trying to draw general conclusions about the properties of galaxies far more distant, for which we have a great deal less information than is available for M31. After struggling to understand the wealth of information available presently on M31, I can only admire the prescient insight of Walter Baade, as I conclude with his words: "We must conclude, then, that in the central region of the Andromeda Nebula we have a metal poor Population II, which reaches -3^{m} for the brightest stars, and that underlying it there is a very much denser sheet of old stars, probably something like those in M67 or NGC 6752. We can be certain that these are enriched stars, because the cyanogen bands are strong, and so the metal/hydrogen ratio is very much closer to what we observe in the sun and in the present interstellar medium than to what is observed for Population II. And the process of enrichment has taken very little time. After the first generation of stars has been formed, we can hardly speak of a 'generation,' because the enrichment takes place so soon, and there is probably very little time difference. So the CN giants that contribute most of the light in the nuclear region of the Nebula must also be called old stars; they are not young."—Baade (1963, p. 256).

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