The Star Formation Histories of the M31 and M33 Spheroids

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Abstract. I review the observational constraints on the star formation histories in the spheroids of M33 and M31, the other two spiral galaxies in the Local Group. M33 does not possess a traditional bulge; instead, it has a small nuclear region hosting stars with a wide range of ages. The star formation history of the M33 halo is poorly constrained, but composite spectra of its halo globular clusters imply a wide age spread of 5–7 years, while the presence of RR Lyrae stars in the halo implies at least some of the population is ancient. Although it is possible to obtain the detailed star formation history of the M33 halo via deep photometry, this has not been done to date. M31 hosts a traditional bulge that is apparently dominated by stars older than 10 Gyr. Deep photometry of the M31 halo demonstrates that it hosts both a population of ancient metal-poor stars and a significant population extending to younger ages and high metallicity, apparently due to its active merger history.

1. Introduction

The Local Group hosts three spiral galaxies: the Milky Way, M31, and M33. The Milky Way and M31 are the only massive galaxies in the Local Group, and there are indications that M31 is more representative of massive spirals than the Milky Way (e.g., Hammer et al. 2007). While M33 is the third most massive galaxy in the Local Group, it is a distant third (van den Berg 2000), and it is representative of the most common type of spiral galaxy in the local universe (see Marinoni et al. 1999). Because M31 and M33 are at respective distances of 770 kpc (Freedman & Madore 1990) and 860 kpc (Sarajedini et al. 2006), we can obtain photometry of their resolved stellar populations and thus constrain their star formation histories at a fidelity exceeding that possible in the Milky Way, where such studies of the field population are often hampered by distance and reddening uncertainties. Here, I review the observational constraints on the spheroid (bulge and halo) populations of these galaxies.

2. Age Constraints

Spheroids are generally dominated by stars older than 1 Gyr. In such populations, changes with age are less dramatic than they are for younger systems. The best age diagnostics come from photometry reaching low-mass (∼0.8 $M_\odot$) main sequence (MS) stars; such photometry enables the reconstruction of the complete star formation history with an age resolution of ∼1 Gyr, but it is difficult to obtain such photometry outside the Milky Way system, due to crowding
and depth limitations. Age constraints are also available through photometry of later evolutionary phases, such as the horizontal branch (HB), asymptotic giant branch (AGB), and red giant branch (RGB); relative to MS stars, these brighter stars can be detected in more distant and crowded regions, but the age resolution is poorer, allowing one to distinguish between young (<3 Gyr), intermediate-age (3–8 Gyr), and old (>8–13 Gyr) stars.

3. M33 Spheroid

The existence of a spheroid in M33 has been controversial for decades. While the galaxy does not appear to have a bulge, it definitely possesses a halo. I discuss these components in turn below.

3.1. M33 Bulge

M33 apparently does not possess a bulge in the classical sense of that term (Bothun 1992), although this has been the subject of debate (e.g., Minniti et al. 1993). Semantics aside, the galaxy hosts a small nucleus that can be fit with a bulge profile that dominates within ~0.1′ of the galaxy center (Stephens & Frogel 2002). In a $K$ vs. $V-K$ color-magnitude diagram (CMD) of the brightest stars in the nucleus, Stephens & Frogel (2002) find young, intermediate-age, and old stars with a mean metallicity $[\text{Fe/H}] = -0.26$. It is not possible to obtain photometry of the low-mass MS stars in the nucleus with any observatory in operation or in development, so the constraints on the star formation history will be poor for the foreseeable future.

3.2. M33 Halo

The existence of a halo in M33 was also controversial in the past, such that the galaxy was sometimes referred to as a “pure disk” galaxy. However, in recent years a preponderance of evidence demonstrated beyond any doubt that M33 hosts a stellar halo. Although some regions of the disk have Hubble Space Telescope (HST) photometry reaching the stellar MS (Program 10190; PI Garnett), the halo-dominated regions beyond the disk have not been imaged at sufficient depth, so the star formation history of the M33 halo remains poorly constrained. Chandar et al. (2002) kinematically segregated the stellar clusters of M33 into disk and halo components. Unresolved photometry and spectroscopy of the clusters enabled a rough age estimate that is prone to degeneracies between blue MS stars and blue HB stars. The young clusters in the sample have motions consistent with disk membership, but the old clusters show a much larger velocity dispersion, implying that 85% belong to the halo and 15% belong to the disk (Figure 1). The clusters with halo kinematics have a spread in relative ages of 5–7 Gyr, much greater than the globular cluster system in the Milky Way halo. Subsequent photometry of one globular cluster in the sample was sufficiently deep to demonstrate that its blue spectrum is due to the presence of blue MS stars and not blue HB stars, proving its age is 5–8 Gyr than the other globular clusters in their sample, but unfortunately the cluster cannot be kinematically assigned to either the disk or halo (Chandar et al. 2006).

Sarajedini et al. (2006) found evidence for a halo using 64 RR Lyrae variables they identified in the galaxy. They estimated reddenings from their mini-
Figure 1. Difference between local disk velocity and measured cluster velocity as a function of age in M33 clusters (Chandar et al. 2002), where cluster age is estimated from integrated photometry and spectroscopy. The spread in age for globular clusters in the M33 halo is much larger than it is for such clusters in the Galactic halo. Plot provided courtesy of R. Chandar.

Minimum $V-I$ colors and metallicities from their periods. The resulting distributions of reddening and metallicity imply they belong to two distinct populations, associated with the disk and halo, providing evidence for these components in the field that complements the evidence in clusters (above). RR Lyrae stars are only present in ancient (>10 Gyr) populations, implying that both the M33 disk and halo host at least some ancient stars. In the [Fe/H] distribution for the halo RR Lyrae stars, the peak is at $-1.3$, although the metallicities of the RR Lyrae stars are not necessarily representative of the underlying population, because metallicity affects the HB temperature distribution and thus the fraction of HB stars falling in the instability strip.

McConnachie et al. (2006) also found evidence for a halo field population. From spectroscopy of 280 stars, they were able to segregate their sample into three components using both kinematics and metallicity: the halo, the disk, and a third unknown component possibly associated with a stellar stream. The halo component exhibits a mean [Fe/H] of $-1.5$ and a velocity dispersion of $\sim 50$ km s$^{-1}$, but the data provide no age constraints.

Using star counts of RGB and AGB stars along the minor axis, Teig (2008) found a break in the surface brightness profile at 11 kpc, where the profile changes from that of an exponential disk to a power-law halo (see also Teig et al. 2009). The CMD of these bright stars implies the halo population is dominated by stars older than 3 Gyr with a mean [Fe/H] of $-1.2$. This is in good agreement with the CMD of Brooks et al. (2004), who obtained $V$ and $I$ photometry in the halo outskirts and found a mean [Fe/H] of $-1.24$.

The next logical step in the investigation of the M33 halo is deep photometry reaching its low-mass MS stars. This is the only way to unambiguously characterize the age distribution in the field population. While such photome-
try has been obtained in multiple regions of the M31 halo with HST (discussed below), the M33 halo remains unexplored, with very loose constraints on its star formation history.

4. M31 Spheroid

While M31 certainly has both a bulge and a halo, the distinction between these components is somewhat muddled in the literature. Historically, studies of the bulge and halo were driven by the appearance of M31 in wide-field shallow imaging (e.g., Walterbos & Kennicutt 1988), with “bulge” studies generally focusing on the region within a kpc of the center, and “halo” studies focusing on regions beyond 10 kpc on the minor axis. However, subsequent studies showed that the spheroid looks like a bulge out to ≈20 kpc in both its surface-brightness profile (Pritchet & van den Bergh 1994) and metallicity distribution (Mould & Kristian 1986; Durrell et al. 1994, 2001). It was only recently discovered that the surface-brightness profile transitions to a power-law (Guhathakurta et al. 2005; Irwin et al. 2005) and the metallicity drops by ≈1 dex (Kalirai et al. 2006) beyond 20 kpc, as expected for a halo. For consistency with historical studies, I will refer to all regions beyond 10 kpc on the minor axis as “halo” despite the persistence of some bulge-like properties out to 20 kpc.

4.1. M31 Bulge

Two fields in the M31 bulge were recently imaged in the near-IR at high resolution using adaptive optics on Gemini North (Davidge et al. 2005), resolving the upper 4–5 mag of the RGB and AGB. The resulting $H$ and $K$ CMDs are consistent with a population dominated by stars at an age of ≈10 Gyr, with a metallicity near solar, although the best-fit models include a minority intermediate-age component that may be spurious (Olsen et al. 2006). As with the center of M33, no observatory in operation or development is capable of obtaining the detailed star formation history of the M31 bulge, because crowding precludes photometry of the low-mass MS stars.

4.2. M31 Halo

Until the past decade, studies of the resolved stellar populations in the M31 halo generally focused on the metallicity distribution (e.g., Mould & Kristian 1986; Durrell et al. 1994, 2001). Metallicity distributions were usually fit by assuming an old age (>10 Gyr) and then comparing the stars on the AGB and RGB to isochrones or globular cluster templates, although some studies were deep enough to reach the HB (e.g., Holland et al. 1996). Although the RGB, AGB, and HB distributions are, in principle, sensitive to age in broad age bins (as noted above), several factors prevented these studies from exploring the age distribution, including photometric scatter, insufficient star counts, and contamination from foreground Milky Way dwarfs.

When the Advanced Camera for Surveys (ACS) was installed on HST in 2002, it became possible to obtain photometry of low-mass MS stars in the M31 halo, enabling the exploration of both the metallicity and age distributions. Brown et al. (2003) imaged a field 11 kpc from the nucleus on the southeast
minor axis, obtaining photometry of 250,000 stars down to $V \sim 30.5$ mag in bands similar to $V$ and $I$ (Figure 2). By providing a large number of stars with small photometric errors on the low-mass MS, the catalog was immune to contamination from foreground Milky Way dwarfs. The resulting fit to the CMD found a wide age range in addition to the wide metallicity range that was already known, and speculated that this was due to a significant merger or series of smaller mergers in the galaxy. In the best-fit model (Brown et al. 2006), ~40% of the stars are younger than 10 Gyr and more metal-rich than 47 Tuc ([Fe/H] = −0.7), with significant numbers of stars down to ages of 2 Gyr. Besides the field population, there is evidence from integrated colors and spectroscopy that the M31 globular cluster system also extends to intermediate ages (Puzia et al. 2005; Beasley et al. 2005).

The recent wide-field imaging surveys of M31 clearly show that it has undergone a violent merger history (Ferguson et al. 2002; Ibata et al. 2007), including a giant stellar stream resulting from the tidal debris of a recent merger event (Ibata et al. 2001). Subsequent studies demonstrated that the inner spheroid of M31 (within ~15 kpc) is polluted by material stripped from progenitor satellite of the giant stellar stream. This evidence includes N-body simulations of the satellite disruption that reproduce the morphology of the major substructures in the galaxy (Fardal et al. 2007), kinematical surveys that confirm the motions in the N-body simulations (Gilbert et al. 2007), and followup ACS imaging of the giant stellar stream that shows strong similarities between the star formation histories of the stream and inner spheroid (Figure 2; Brown et al. 2006).

Given the discovery that the M31 halo becomes more like a halo beyond 20 kpc, a subsequent ACS survey explored regions on the minor axis further out, at 21 kpc (in the transition region; Brown et al. 2007) and 35 kpc (where the spheroid clearly exhibits a halo surface brightness profile and metallicity; Brown et al. 2008). Compared to the field at 11 kpc, these fields host far fewer stars at ages younger than 8 Gyr, but the populations clearly do not represent a classical halo formed via monolithic collapse at early times (Figure 2); in the best-fit model, ~30% of the stars are younger than 10 Gyr, and only ~10% of the stars are ancient (>12 Gyr) and metal-poor ([Fe/H] ≤−1.5). All regions of the halo explored to date are consistent with a history whereby the galaxy forms over a prolonged period of hierarchical merging.

5. Summary

M33 possesses a halo but not a traditional bulge. This halo exhibits secondary evidence for intermediate-age populations, such as a halo globular cluster system spanning a wide age range in integrated spectroscopy (Chandar et al. 2002), but the age distribution in the M33 halo has not been constrained via photometry of the low-mass MS stars, as done in M31. Thus, our understanding of the star formation history in the M33 halo is in a state similar to that found in M31 prior to the advent of the HST ACS. For years, M31 was assumed to host an old halo of age >10 Gyr. The M31 halo has now been probed in multiple locations along the minor axis, spanning the regions where the halo looks more like a bulge and where it looks more like a traditional halo, but in all of these regions it exhibits an extended star formation history (Brown et al. 2006, 2007, 2008). The M33 halo
remains the last spiral galaxy halo unexplored via photometry of its low-mass MS stars, leaving its star formation history poorly constrained. Appropriately deep imaging of the M33 halo should be obtained during the remaining HST mission, or it may be many years before such data can be obtained again.

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Figure 2. Radial velocities (top row; dotted line is M31 systemic velocity), CMDs (middle row; curve shows 47 Tuc ridge line for comparison), and star formation histories (bottom row; area of circles proportional to weight in fit) for four regions in the M31 halo (Brown et al. 2003, 2006, 2007, 2008). The three regions on the minor axis (at 11, 21, and 35 kpc) show a kinematically hot population at the M31 systemic velocity, while the off-axis field shows the kinematically cold stream plunging into M31 toward us from behind the galaxy. Despite their distinct kinematic profiles, the CMDs and associated star formation histories for the 11 kpc field and the stream are very similar, due to the inner halo being polluted by debris from the stream’s progenitor (Brown et al. 2006; Fardal et al. 2007; Gilbert et al. 2007). Although the fields further out on the minor axis do not include significant numbers of stars as young and metal-rich as those found in the 11 kpc and stream fields, all of the halo fields exhibit an extended star formation history, consistent with expectations from hierarchical merging.