STELLAR POPULATIONS IN THE OUTER HALO OF THE MASSIVE ELLIPTICAL M49

J. Christopher Mihos1, Paul Harding1, Craig S. Rudick2, and John J. Feldmeier3
1 Department of Astronomy, Case Western Reserve University, 10900 Euclid Ave, Cleveland, OH 44106, USA; mihos@case.edu, paul.harding@case.edu
2 Institute for Astronomy, ETH Zurich, CH-8093 Zurich, Switzerland; craig.rudick@phys.ethz.ch
3 Department of Physics and Astronomy, Youngstown State University, Youngstown, OH 44555, USA; jjfeldmeier@ysu.edu

Received 2012 December 21; accepted 2013 January 17; published 2013 February 1

ABSTRACT

We use deep surface photometry of the giant elliptical M49 (NGC 4472), obtained as part of our survey for diffuse light in the Virgo Cluster, to study the stellar populations in its outer halo. Our data trace M49’s stellar halo out to ~100 kpc (7r_e), where we find that the shallow color gradient seen in the inner regions becomes dramatically steeper. The outer regions of the galaxy are quite blue (B − V ∼ 0.7); if this is purely a metallicity effect, it argues for extremely metal-poor stellar populations with [Fe/H] < −1. We also find that the extended accretion shells around M49 are distinctly redder than the galaxy’s surrounding halo, suggesting that we are likely witnessing the buildup of both the stellar mass and metallicity in M49’s outer halo due to late time accretion. While such growth of galaxy halos is predicted by models of hierarchical accretion, this growth is thought to be driven by more massive accretion events which have correspondingly higher mean metallicity than inferred for M49’s halo. Thus the extremely metal-poor nature of M49’s extended halo provides some tension against current models for elliptical galaxy formation.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: halos – galaxies: individual (M49) – galaxies: stellar content

Online-only material: color figures

1. INTRODUCTION

Mounting evidence suggests that elliptical galaxies grow through a two-phase process. The rapid assembly of gas-rich clumps at high redshift likely results in a highly dissipative collapse process not too dissimilar to “monolithic collapse” models for elliptical galaxy formation. This leads to the formation of dense, compact spheroidal galaxies (Khochfar & Silk 2006), similar to objects seen in recent high-redshift galaxy surveys (e.g., Zirm et al. 2007; van Dokkum et al. 2008). These systems are significantly more compact than local ellipticals, and need to grow in size to become the ellipticals we see today. This argues for a second assembly phase involving later accretion of low-mass objects with higher specific angular momentum in order to build up the outer envelopes of the growing ellipticals (e.g., Naab et al. 2007; Oser et al. 2012).

Under this hierarchical model, the outskirts of nearby elliptical galaxies should harbor a variety of signatures of this formation process. Dissipative collapse should lead to strong metallicity gradients (Carlberg 1984; Arimoto & Yoshii 1987), but mergers effectively mix the inner galaxy and largely wash out the gradients (White 1980; Mihos & Hernquist 1994). However, since this mixing is not perfect, the outer halos should still retain a truly metal-poor population of stars. Subsequent accretion of low-mass galaxies would then deposit stars with a broad range of metallicities into the outer halo, building up the halo’s surface brightness and mean metallicity. Unlike the rapid mixing in the inner regions, the low density and larger dynamical timescales in galaxy outskirts mean that the morphological signatures of accretion—shells and streams of stars—survive longer at large radius. Indeed, a variety of deep imaging studies show that many ellipticals have extended tidal debris from late accretion events (e.g., Malin & Carter 1983; Tal et al. 2009; Janowiecki et al. 2010).

While the structure of elliptical galaxy halos can be probed by deep imaging, their extremely faint surface brightness makes detailed studies of their stellar populations difficult. For sufficiently nearby ellipticals, the discrete stellar populations can be imaged using the Hubble Space Telescope (HST), giving strong constraints on the age and metallicity of the stars (e.g., Rejkuba et al. 2005, 2011; Harris et al. 2007). Stellar populations in more distant ellipticals must be studied using their integrated colors or spectra. These studies generally show that ellipticals have a gradual radial decline in the mean metallicity over the inner few effective radii (r_e), with gradients of d [Fe/H]/d log (r) ∼ −0.1 to −0.3 (e.g., Peletier et al. 1990; Kobayashi & Arimoto 1999). However, most studies generally do not probe the outer halo, where the stellar populations may have quite sub-solar metallicities. Moreover, as the most massive ellipticals tend to live near the center of galaxy clusters, studies of their outer halos are complicated by contamination from the more extended intracluster starlight (ICL) surrounding them. As such, the chemical abundance constraints contained in the outer halos of giant ellipticals have remained largely untapped. In this Letter, we present deep imaging of the massive elliptical M49 (log M* = 11.9; Côté et al. 2003), which lives in the outskirts of the Virgo Cluster where ICL contamination is minimized, to study the stellar populations in its outer halo. 4

2. OBSERVATIONS

We observed M49 as part of our deep imaging survey of diffuse light in the Virgo Cluster using Case Western Reserve University’s 24/36’ Burrell Schmidt telescope. We give a brief description of the data set here; more details can be found in our earlier papers (Mihos et al. 2005; Janowiecki et al. 2010; Rudick et al. 2010). Fields around M49 were imaged in spring 2006 and 2007 in Washington M, and again in spring 2011 in a custom B filter; these filters are similar to standard Johnson B and V, but ~300 Å bluer. Each data set consists of a large number of...
overlapping images with individual exposure times of 1200 s in B and 900 s in M, yielding sky levels of $\sim$800 and 1300 ADU, respectively. The images were flat-fielded using a night-sky flat constructed from 50–100 offset blank sky pointings. After subtracting the extended wings of bright stars and masking discrete sources on each image (stars, background galaxies, and the bright inner regions of large galaxies), sky subtraction was achieved by subtracting planes fit to the unmasked background sky.

The photometric transformation to Johnson B and V magnitudes was derived using Landolt UBVRI standards to measure the filter color terms, and the $\sim$200 stars on each frame with accurate Sloan Digital Sky Survey photometry to derive the photometric zero points (employing the Lupton (2005) ugriz to Johnson transformation). The solutions showed a residual scatter of 0.02–0.03 mag in the photometry of individual stars and 0.01 mag scatter in the frame-to-frame zero points. The individual images were then scaled to a common zero point and median combined into final B and V mosaics. In these mosaics, there are typically 30–50 and 40–90 images contributing to any given pixel in the B and V mosaics, respectively.

At low surface brightness, accurate background subtraction and noise estimation is critical to measurements of surface brightness and color. To estimate and correct for uncertainty in the residual background around M49, we identify 50 circular background apertures, 1.5′ in radius, located 30′–60′ from M49’s center (beyond the area shown in Figure 1). In these regions, the average residual background is +0.4 ADU in B and −1.0 ADU in V, with 1σ per-pixel noise of 0.75 and 1.0 ADU in B and V, respectively. This gives us 2.5σ limiting surface brightness of $\mu_{B,\text{lim}} = 28.7$ and $\mu_{V,\text{lim}} = 28.3$, and we correct the photometric data for Galactic extinction using values of $A_V = 0.061$ and $A_B = 0.081$ (Schlafly & Finkbeiner 2011).

Finally, to increase signal-to-noise at low surface brightness, the B and V mosaics were masked and spatially rebinned to 13″ resolution. In this process, discrete objects on the mosaic were again masked, after which the mosaics were rebinned into 9 × 9 pixel (13″ × 13″) bins, calculating the median intensity of the unmasked pixels in each bin. In the analysis that follows, the full resolution mosaics are used to measure the photometric properties of M49’s inner high surface brightness regions, while the rebinned mosaics are used at larger radius and lower surface brightness.

3. RESULTS

Figure 1 shows our V image of M49 (top) along with a residual image (middle) adapted from Janowiecki et al. (2010), constructed by subtracting an elliptical model of M49’s light profile. A number of accretion shells and streams can be seen surrounding M49; these are discussed in more detail in Janowiecki et al. (2010) and have been subsequently confirmed by Arrigoni Battaia et al. (2012). The bottom panel of Figure 1 shows our new $B - V$ color map of M49, binned to 13″ × 13″ resolution. In this image, we have “unmasked” the high surface brightness regions of the galaxies to give visual continuity to the image and show color across all surface brightnesses.

M49’s color gradient can be clearly seen in the image, with colors ranging from $B - V \sim 1$ at 15″ to $B - V < 0.7$ in the outskirts (r > 1000″). Projected on the face of M49 are two blue star-forming companions, VCC1249 5′ to the southeast and NGC 4470 10′ to the south. To the northwest of M49, the extended debris shell seen in the residual map can also be seen in the color map; the shell region is redder than the rest of

M49’s halo at similar radius ($r_{\text{sma}} = 20′$ or 90 kpc). In contrast, the shells to the southeast do not show any noticeable features in the color map. This is not surprising as these shells are at smaller radius ($r_{\text{sma}} = 12′.5$ or 60 kpc), where M49’s halo is
both brighter and redder. The southeastern shells contribute less light to the color signal here and, if they are similar in color to M49’s halo at that radius.

To extract the quantitative color profile of M49, we first mask M49’s companion galaxies out to their $\mu_V \sim 28.5$ mag arcsec$^{-2}$ isophote as measured in the residual image in Figure 1. We then calculate the median surface brightness and color of all unmasked pixels in elliptical annuli of constant ellipticity $\epsilon = 0.28$ and position angle P.A. $= -31$ (Kormendy et al. 2009; Janowiecki et al. 2010). Measured this way, the derived surface brightness and color are areal-weighted rather than luminosity-weighted, and should be more indicative of the diffuse halo, unbiased by contamination from any discrete unmasked objects that fall within the annuli. The quartile error bars on the outer points reflect the effects of background subtraction uncertainty, and are calculated by bootstrap sampling the background apertures and recalculating the profiles for each background estimate.

M49’s color profile (Figure 2) shows a very shallow gradient in the inner regions which becomes much steeper at large radius. Inside of $r = 100''$ (8 kpc), the logarithmic color gradient is $\Delta(B-V) \equiv d(B-V)/d \log r = -0.03$ mag dex$^{-1}$, but the gradient steepens continuously with radius, reaching values of $-0.3$ mag dex$^{-1}$ out at $r = 800''$ (64 kpc). At the outermost point we measure, the color has dropped to an extremely blue $B-V = 0.66 \pm 0.02$.

Inside an effective radius, our photometry compares well to previously published data for M49, all of which show a systematic bluing of the colors with increasing radius. Our $B-V$ colors and gradient match those measured by Idiart et al. (2003), and, assuming old stellar populations, are commensurate with gradients measured in other optical colors (Bender & Moellenhofff 1987; Peletier et al. 1990; Kim et al. 2000). At larger radius, however, the situation becomes more complicated.

Cohen (1986) measure continual bluing in $g - i$ out to $\sim 350''$, but a reddening in $g - r$, while Kim et al. (2000) show a gradual reddening from 200''to 500'' in $C - T_1$. At these radii, M49’s surface brightness is well below the sky, making the derived color gradients very sensitive to accurate sky subtraction. In our data, however, the rapid change in slope becomes clearly noticeable at 30 kpc ($2r_e$), where the sky uncertainty is only $\sim 1\%$ of the measured surface brightness. Even in our outermost radial bin, the surface brightness is a magnitude above the per-pixel sky noise, and the error bars on those points reflect the effects of the global sky uncertainty. Clearly, errors in sky subtraction are not the cause of the rapid bluing we see at large radius in M49.

4. DISCUSSION

Color trends in elliptical galaxies—both radial gradients within galaxies and trends between color and luminosity in galaxy populations—are well established to be driven largely by metallicity effects. Figure 3 shows the relationship between the $B - V$ color and metallicity for single stellar population (SSP) models from Bruzual & Charlot (2003), using a Chabrier initial mass function and Padova isochrones. For [Fe/H] $> -1$ and populations older than a few Gyr, our inner color gradient translates to a metallicity gradient of $\Delta$[Fe/H] $= -0.15$ dex dex$^{-1}$, similar to the metallicity gradient derived by Peletier et al. (1990) using $B - R$ colors, but somewhat more shallow than those derived spectroscopically, which suggest metallicity gradients of $-0.2$ to $-0.3$ dex dex$^{-1}$ (Kobayashi & Arimoto 1999). The gradient steepens in the outskirts; if interpreted solely as a metallicity effect, by the inferred gradient reaches $\Delta$[Fe/H] $= -2$ to $-3$ dex dex$^{-1}$ by 1000''. The rapid steepening of the color profile begins at approximately the same radius where the luminosity profile begins to show excess light above a pure $r^{1/4}$ law, perhaps suggesting that instead of a simple steepening of the metallicity gradient, we may be seeing a more
discrete transition from a metal-rich component to a metal-poor component (e.g., Harris et al. 2007). For old populations, metallicities in the range $[\text{Fe/H}] = −1$ to $−1.5$ are needed to explain the extremely blue colors of the outer isophotes, metallicities similar to those of M49’s metal-poor globular cluster system ($[\text{Fe/H}] \sim −1.3$; Geisler et al. 1996; Cohen et al. 2003).

In principle, the steep gradient could also be explained by systematically younger population ages at large radius. If we extrapolate the shallow inner metallicity gradient outward, we would expect metallicities in the outer halo of $[\text{Fe/H}] \sim −0.15$ to $−0.3$. At these metallicities, the only way to match the outer isophotal colors is using stellar populations with SSP-equivalent ages of $≈2$ Gyr (Figure 3). This is unrealistically small; while recent accretion events can deposit stars of varying age and metallicity to the outer halo, leading to wider diversity in the halo stellar populations.

Indeed, our photometry directly shows the effect of satellite accretion on the halo populations in M49. The NW Shell is $0.07$ mag redder than the surrounding halo; since this region consists of light from both the shell and from M49’s (bluer) halo, the intrinsic color of the Shell must be even redder, with $B − V \sim 0.85$. The fact that the shells are redder than the surrounding halo can be understood in terms of a disruptive accretion event. Because of the mass–metallicity relationship, the mean color of the accreted satellite will be bluer than that of M49 as a whole, but can be redder than M49’s outer halo. For example, van Zee et al. (2004) show that the population of dEs in Virgo has a mean $B − V$ color of $0.77$ at $r_g = 15$ (roughly $1\%$ the luminosity of M49); if a system like these were accreted by M49, it would leave a shell system much like what is shown in Figure 1.

In the picture painted here, M49’s metal-poor halo is a relic of the rapid early assembly of the galaxy, while ongoing accretion (as seen in the tidal shells) continues to build the halo mass and metallicity over time. However, this scenario is not without problems. With a velocity dispersion of $280$ km s$^{-1}$ and effective radius of $15$ kpc, M49 sits squarely on the mass–size relationship for galaxies in the local universe (van der Wel et al. 2008). In other words, M49 has already built its halo to modern-day standards, but has done so while retaining its metal-poor nature. Simulations suggest that the dominant mode of halo growth is via minor mergers with typical mass ratios of $1:5$ most age estimates tend to yield older ages in the outer halo (8–12 Gyr; Baes et al. 2007; Greene et al. 2012). In cases where younger ages are inferred, there is evidence for a recent accretion event in the galaxy’s halo (e.g., NGC 3348; Baes et al. 2007). While our data suggest that M49’s outskirts are at the extreme end of the inferred age/metallicity ranges in these other studies, we stress the very large radii being probed; restricting our analysis to the inner few $r_e$ would show only a modest population gradient similar to those previously determined.

For a few nearby ellipticals, additional information comes from HST studies of resolved stellar populations in their outer halos. NGC 5128 (Centaurus A) shows a mean metallicity of $[\text{Fe/H}] = −0.5$ at $r = 40$ kpc ($7r_e$; Rejkuba et al. 2005), while NGC 3379 shows an extremely broad metallicity distribution at $r = 33$ kpc ($12r_e$) with a mean metallicity of $[\text{Fe/H}] = −0.7$ (Harris et al. 2007). These metallicities are comparable to what we infer (assuming old stellar populations) for M49 at similar physical radius ($r = 30–40$ kpc), but higher when compared at similar scaled radius ($r/r_e \sim 10$). NGC 5128 also shows evidence for a second population of younger stars (ages $\sim2–4$ Gyr) in its stellar halo (Rejkuba et al. 2011), likely related to the galaxy’s status as a post-accretion system. However, these young stars comprise at most $10\%$ of the mass of the halo, and the inferred integrated $B − V$ color of NGC 5128 would still be redder than what we observe in the outskirts of M49.

Theoretical expectations for the stellar populations of elliptical halos are similarly diverse. While an initial dissipative collapse should yield strong metallicity gradients (Larson 1974; Carlberg 1984; Arimoto & Yoshii 1987), subsequent merging effectively mixes the inner regions (White 1980; Mihos & Hernquist 1994; Kobayashi 2004), leaving behind the weak gradients observed inside a few $r_e$. However, chemodynamic simulations of elliptical galaxy formation (Kobayashi 2004) show that the outer metallicity gradients can remain quite steep, yielding metallicities of $[\text{Fe/H}] < −1$ at large radius. Of course, additional accretion of satellite systems can deposit stars of varying age and metallicity to the outer halo, leading to wider diversity in the halo stellar populations.
(Oser et al. 2012); such mergers likely would have deposited stars with significantly higher metallicity than that inferred for M49’s halo. This tension between a fully developed halo and its low metallicity remains unresolved.

It is interesting in this context to compare M49 to M87, the giant elliptical at the heart of Virgo. While the two galaxies are comparable in luminosity, M87 has a higher Sérsic index \( n = 11.8 \), compared to M49’s \( n = 6.0 \); Kormendy et al. (2009) and flatter color gradient (Rudick et al. 2010) at a larger radius than M49. Where it sits, M87 is also subject to a constant bombardment of satellite galaxies; this dynamically active environment continually adds material to M87’s outer halo, as well as the ICL around M87 (Mihos et al. 2005), resulting in the more extended envelope with relatively high mean metallicity. In contrast, M49 lies on the outskirts of the Virgo Cluster, projected 1.2 Mpc from the cluster center, and its halo may be falling into Virgo for the first time (Irwin & Sarazin 2010). As such, its halo could be more indicative of ellipticals in field and group environments, and be less “processed” than cluster ellipticals.

Stellar populations in the halos of ellipticals hold important information on the processes shaping today’s elliptical galaxies. If M49’s extended but extremely metal-poor halo is a common feature in massive ellipticals, a revision of galaxy formation models may be necessary. Progress on these issues requires a better census of the halo stellar populations in ellipticals. Unfortunately, broadband colors are a very blunt tool for constraining stellar populations, unsuited for disentangling age and metallicity effects, while the very low halo surface brightness makes imaging far down the red giant branch to provide constraints on the stellar populations, and has been used to study the metallicity distribution in Virgo’s intracluster light (Ferguson et al. 1998; Durrell et al. 2002, 2008; Williams et al. 2007). A similar study of the outer halos of M49 and other Virgo ellipticals, as well as ellipticals in the nearby field, would provide a direct test of the extremely metal-poor populations inferred from our deep imaging, and open up a new avenue for the study of elliptical galaxies.

This work has been supported by the NSF through grants AST-0607526 and AST-1108964 to J.C.M. and AST-0807873 to J.J.F. We thank Heather Morrison, Scott Trager, and Antonio Pipino for many useful discussions.

Facility: CWRU:Schmidt

REFERENCES

Arimoto, N., & Yoshii, Y. 1987, A&A, 173, 23
Arrigoni Battaia, F., Gavazzi, G., Fumagalli, M., et al. 2012, A&A, 543, A112
Baes, M., Sil’chenko, O. K., Moiseev, A. V., & Manakova, E. A. 2007, A&A, 476, 991
Bender, R., & Moellenhoff, C. 1987, A&A, 177, 71
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Carlberg, R. G. 1984, ApJ, 286, 416
Cohen, J. G. 1986, AJ, 92, 1059
Cohen, J. G., Blakeslee, J. P., & Côté, P. 2003, ApJ, 592, 866
Côté, P., McLaughlin, D. E., Cohen, J. G., & Blakeslee, J. P. 2003, ApJ, 591, 850
Durrell, P. R., Ciardullo, R., Feldmeier, J. J., Jacoby, G. H., & Sigurdsson, S. 2002, ApJ, 570, 119
Ferguson, H. C., Tanvir, N. R., & von Hippel, T. 1998, Natur, 391, 461
Foster, C., Proctor, R. N., Forbes, D. A., et al. 2009, MNRAS, 400, 2135
Geisler, D., Lee, M. G., & Kim, E. 1996, AJ, 111, 1529
Greene, J. E., Murphy, J. D., Comerford, J. M., Gebhardt, K., & Adams, J. J. 2012, ApJ, 750, 32
Harris, W. E., Harris, G. L. H., Layden, A. C., & Wehner, E. M. H. 2007, ApJ, 666, 903
Hernquist, L., & Quinn, P. J. 1989, ApJ, 342, 1
Idiart, T. P., Michel-Dansac, L., & de Freitas Pacheco, J. A. 2003, A&A, 398, 949
Irwin, J. A., & Sarazin, C. L. 1996, ApJ, 471, 653
Janowiecki, S., Mihos, J. C., Harding, P., et al. 2010, ApJ, 715, 972
Khochfar, S., & Silk, J. 2006, ApJL, 648, L21
Kim, E., Lee, M. G., & Geisler, D. 2000, MNRAS, 314, 307
Kobayashi, C. 2004, MNRAS, 347, 740
Kobayashi, C., & Arimoto, N. 1999, ApJ, 527, 573
Kormendy, J., Fisher, D. B., Cornell, M. E., & Bender, R. 2009, ApJS, 182, 216
Larson, R. B. 1974, MNRAS, 169, 229
Lupton, R. T., 2005, http://www.sdss3.org/dr8/algorithms/sdssUBVRITransform.php#Lupton2005
Malin, D. F., & Carter, D. 1983, ApJ, 274, 534
Mei, S., Blakeslee, J. P., Côté, P., et al. 2007, ApJ, 655, 144
Mihos, J. C., Harding, P., Feldmeier, J., & Morrison, H. 2005, ApJL, 631, L41
Mihos, J. C., & Hernquist, L. 1994, ApJ, 427, 112
Naab, T., Johansson, P. H., Ostriker, J. P., & Efstathiou, G. 2007, ApJ, 658, 710
Oser, L., Naab, T., Ostriker, J. P., & Johansson, P. H. 2012, ApJ, 744, 63
Peletier, R. F., Davies, R. L., Illingworth, G. D., Davis, L. E., & Cowan, M. 1990, AJ, 100, 1091
Rejkuba, M., Greggio, L., Harris, W. E., Harris, G. L. H., & Peng, E. W. 2005, ApJ, 631, 262
Rejkuba, M., Harris, W. E., Greggio, L., & Harris, G. L. H. 2011, A&A, 526, A123
Rudick, C. S., Mihos, J. C., Harding, P., et al. 2010, ApJ, 720, 569
Schlafly, E., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Tal, T., van Dokkum, P. G., Nelan, J., & Bezanson, R. 2009, AJ, 138, 1417
van der Wel, A., Holden, B. P., Zirm, A. W., et al. 2008, ApJ, 688, 48
van Dokkum, P. G., Franx, M., Kriek, M., et al. 2008, ApJL, 677, L5
van Zee, L., Barton, E. J., & Skillman, E. D. 2004, AJ, 128, 2797
Weijmans, A.-M., Cappellari, M., Bacon, R., et al. 2009, MNRAS, 398, 561
White, S. D. M. 1980, MNRAS, 191, 1P
Williams, B. F., Ciardullo, R., Durrell, P. R., et al. 2007, ApJ, 656, 756
Zirm, A. W., van der Wel, A., Franx, M., et al. 2007, ApJ, 656, 66