The Metallicity of Diffuse Intrahalo Light

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ABSTRACT

We make predictions for the metallicity of diffuse stellar components in systems ranging from small spiral galaxies to rich galaxy clusters. We extend the formalism of Purcell et al. (2007), in which diffuse stellar mass is produced via galaxy disruption, and we convolve this result with the observed mass-metallicity relation for galaxies in order to analyze the chemical abundance of intrahalo light (IHL) in host halos with virial mass \(10^{10.5} M_\odot \leq M_{\text{host}} \leq 10^{15} M_\odot\). We predict a steep rise of roughly two dex in IHL metallicity from the scales of small to large spiral galaxies. In terms of the total dynamical mass \(M_{\text{host}}\) of the host systems under consideration, we predict diffuse light metallicities ranging from \(Z_{\text{IHL}} \lesssim -2.5\) for \(M_{\text{host}} \sim 10^{11} M_\odot\), to \(Z_{\text{IHL}} \sim -1.0\) for \(M_{\text{host}} \sim 10^{12} M_\odot\). In larger systems, we predict a more shallow rise in this trend with \(Z_{\text{IHL}} \sim -0.4\) for \(M_{\text{host}} \sim 10^{13} M_\odot\), increasing to \(Z_{\text{IHL}} \sim 0.1\) for \(M_{\text{host}} \sim 10^{15} M_\odot\). This behavior is coincident with a narrowing of the intrahalo metallicity distribution as host mass increases. The observable distinction in surface brightness between old, metal-poor IHL stars and more metal-rich, dynamically-younger tidal streams is of crucial importance when estimating the chemical abundance of an intrahalo population with multiple origins.

Key words: Cosmology: theory – galaxies: formation – galaxies: evolution – clusters: diffuse light

1 INTRODUCTION

Diffuse stellar components are ubiquitous phenomena that include the intrachannel light at the centers of rich galaxy clusters as well as the diffuse stellar halos that surround individual galaxies like the Milky Way. This diffuse luminosity comprises \(\lesssim 1 - 5\%\) of the total luminosity of spiral galaxies (Morrison et al. 2000; Chiba & Beers 2000; Yanny et al. 2000; Ivezić et al. 2000; Siegel et al. 2002; Irwin et al. 2003; Guhathakurta et al. 2003; Kalirai et al. 2003; Chapman et al. 2003) and as much as \(\sim 10 - 40\%\) of the luminosity of rich galaxy clusters (Calcánio-Redián et al. 2000; Lin & Mohr 2004; Feldmeier et al. 2004; Mihos et al. 2003; Zibetti et al. 2003; Krick et al. 2006; Seigar et al. 2006). Whether in clusters or surrounding individual galaxies, we refer to this diffuse material as “intra-halo light” (IHL). In the prevailing theory of structure formation, objects are built hierarchically through sequential mergers of smaller objects. This provides a natural means of IHL production via the disruption of merging galaxies (Gallagher & Ostriker 1972; Merritt 1983; Byrd & Valtonen 1990; Dubinski et al. 2003; Gnedin 2003; Mihos 2004; Murante et al. 2004; Lin & Mohr 2004). This mechanism includes the emergence of diffuse stellar halos about galaxies such as the Milky Way, resulting from the merger and destruction of dim, dwarf-sized galaxies (Searle & Zinn 1978; Johnston et al. 1994; Johnston 1998; Helmi et al. 1999; Bullock et al. 2001; Johnston et al. 2001; Bullock & Johnston 2004; Robertson et al. 2005; De Lucia & Helmi 2008), making the IHL a potentially rich testbed for structure and galaxy formation theories. In a previous paper, we made predictions for the relative prominence of the IHL as a function of both the total mass of the system (including luminous and dark matter) and the luminosity of the brightest object in each system for systems ranging from dwarf galaxies to rich clusters (Purcell et al. 2007). In this paper we seek to add to the discriminatory power of the IHL as a test of galaxy formation models by making predictions for the metallicities of IHL components in such systems.

Observations of intrachannel light in Abell 3888 indicate that the stellar population composing it has a metallicity distribution function peaking near \(Z \sim 1.0\) in the outer regions of the diffuse component, and \(0.2 \leq Z \leq 0.5\) in the inner region (Krick et al. 2006), although there is large uncertainty in both values stemming from chemical evolution systematics and color analysis. Conservatively, we can say that the chemical abundance of intrahalo stellar
Figure 1. The global mass-to-light $M/L_c$ ratio as a function of host halo mass $M_{\text{halo}}$. The solid line shows the $M/L_c$ result obtained by van den Bosch et al. (2007) for the WMAP1 cosmological parameters. For comparison with the model of PBZ07, the dotted line represents that work’s fiducial $M/L_c$ as drawn from Yang et al. (2003).

Material in cluster-sized host systems is at least one order of magnitude greater than that of the diffuse stellar components around large spirals. M31’s pressure-supported halo has an approximate iron abundance of $[\text{Fe/H}] \sim -1.4$ (Chapman et al. 2006, see also Kalirai et al. 2006), and it resembles the Milky Way halo both kinematically and structurally. The Milky Way’s halo stars are also metal-poor at around $[\text{Fe/H}] \sim -1.5$ (e.g., Ryan & Norris 1991). However, M33’s halo has proven elusive as there is only tentative evidence for a non-rotating, power-law diffuse component at roughly $[\text{Fe/H}] \sim -1.5$ (Ferguson 2007, see also McConnachie et al. 2006 for spectroscopic field analysis).

Numerical simulations indicate that the shredding of infalling galaxies during the hierarchical merging process of host halo formation is a prevalent contributor to diffuse light in clusters (Willman et al. 2004; Rudick et al. 2006; Sommer-Larsen 2006). There is often sufficient stellar mass in this component to dominate the light emitted by the bright central galaxy in the cluster (Conroy et al. 2007, see Gonzalez et al. 2003; Seigar et al. 2006 for observational evidence supporting this prediction). Likewise, simulations of Galaxy formation support the accumulation of a spheroidal stellar halo via the accretion and disruption of dwarf-type satellite galaxies during the construction of the primary system (Dietrich et al. 2003; Read et al. 2003; Font et al. 2006; Abadi et al. 2004).

Our aim in this paper is to predict the metallicity of intrahalo light as a function of the total mass of the system. We explore the behavior of any trends in metallicity as a function of properties of disrupted progenitor systems, in order to discriminate bright diffuse streams from dynamically-older and more well-mixed tidal debris. This debris is created from an enormous dynamic range in halo mass. In addition, the system-to-system scatter in the fraction of luminosity in IHL and IHL metallicities is significant, indicating that large samples are needed in order to study IHL metallicity trends as a function of mass. These factors make direct simulation of IHL production a computationally costly endeavor that is impractical for our purposes, particularly given the inherent uncertainties in numerical treatments of baryonic processes. As an alternative, we rely on the analytic treatment prescribed by Zentner et al. (2005, see below) in order to follow the coalescence of small systems into larger composite systems. This approach models the merging rates and subsequent interactions, including heating and disruption, of systems in an approximate way but with the benefit of being a computationally inexpensive approach that can be used to minimize statistical (not systematic) uncertainties in model predictions. We assume that the stellar material in a merging galaxy will be diffused into the intrahalo light of the larger system when the galaxy’s parent subhalo is significantly affected by tidal and heating processes. Direct treatments of baryonic processes and star formation are uncertain at present. As such, we employ a “bootstrap” approach that feeds the observed mass-metallicity relation for galaxies into our calculation. After determining the stellar contents of disrupted, merging halos according to the empirically-constrained model of Purcell et al. (2007, see below), we assign these stars a metallicity based on the observed mass-metallicity relation. The metallicities of all stars distributed throughout the diffuse light by all merging and disrupted systems are used to obtain the oxygen abundance $[O/H]_{\text{IHL}}$ of diffuse intrahalo light as a function of the total mass of the system $M_{\text{host}}$. At this time, detailed and robust predictions remain beyond the reach of theoretical modelling, so we emphasize (as we did in our previous study, Purcell et al. 2007) that our goal is to highlight gross trends that should be expected in hierarchical models on very general grounds.

In the next section, we outline our model for IHL metallicities. In §3 we present our results and discuss their implications in the context of observational benchmarks in chemical abundance measurements of galactic stellar halos as well as intragroup/intracluster luminosity. Throughout this work, we adopt a ΛCDM cosmological model with $h = 0.7$, $\Omega_m = 1 - \Omega_\Lambda = 0.3$, and a primordial power spectrum which is scale-invariant, $n = 1$, and normalized to $\sigma_8 = 0.9$.

2 METHODS

We investigate the metallicity of tidally-disrupted, diffuse stellar material as a function of host dark matter halo mass. In our terminology, we refer to the largest dark matter halo surrounding a group or cluster of galaxies as the “host” dark matter halo and the smaller halos that are themselves contained within the host but self-bound systems as “subhalos.” Our study expands upon the model of Purcell et al. (2007, hereafter PBZ07), which makes statistical predictions for the stellar mass fraction expected in a diffuse, luminous intrahalo component, over a wide range of host halo mass ($10^{10.5} M_\odot \leq M_{\text{host}} \leq 10^{15} M_\odot$). We give a brief outline of the relevant features of this model here. A more complete
discussion of our modeling techniques and definitions can be found in PBZ07.

Our treatment utilizes the halo formation model of Zentner et al. (2005), for an earlier version see Zentner & Bullock (2003) in order to track the accretion, evolution, and possible destruction of dark matter subhalos analytically. The model of Zentner et al. (2005) produces mass accretion histories over a wide range in host halo mass according to the extended Press-Schechter (EPS) formalism (Bond et al. 1991; Lacey & Cole 1993, for a recent review see Zentner 2007), using the specific implementation described by Somerville & Kolatt (1999), and then uses analytic prescriptions for dynamical friction and mass loss due to interactions within the larger host potential to evolve the population of accreted subhalos. This model is very well-tested against dissipationless cosmological simulations, reproducing a variety of subhalo statistics predicted by direct numerical techniques accurately. We encourage the reader to refer to Zentner et al. (2005) for more detail on this aspect of our model.

Applying observational constraints from galaxy survey data, PBZ07 assign subhalo luminosities according to the results obtained by Yang et al. (2003, see below) in their analysis of the conditional luminosity function of galaxies in the Two-Degree Field Galaxy Redshift Survey (2dFGRS). The model of PBZ07 then implements a critical mass-loss threshold at which orbiting subhalos are considered to be completely tidally shredded when their circular velocities fall below a critical fraction of their maximum circular velocity they had upon accretion into the host, \( f_{\text{crit}} = V_{\text{crit}}/V_{\text{max}}(t_{\text{acc}}) \). A second free parameter \( \alpha \) describes the star formation history of the subhalo, in order to determine its stellar-mass content upon accretion and the subsequent truncation of star formation via ram pressure stripping induced by the host halo’s hot gas. Both parameters are tuned such that contemporary populations of surviving galaxies are recovered by the fiducial model across the host mass scales of interest, and it is instructive to note that the results are insensitive to dramatic changes in these values, which are set to \( f_{\text{crit}} = 0.6 \) and \( \alpha = 1 \). We ignore contributions made to a system’s diffuse light by surviving satellites, as simulations indicate that subhalos are typically disrupted shortly after their stars become tidally stripped in any substantial sense (Bullock & Johnston 2005).

The global variance in the mass-to-light ratio of dark halos as a function of host mass, as obtained by Yang et al. (2003) and discussed in §2.1 convolved with the EPS formalism’s prediction that host halos are chiefly built by the accretion of subhalos roughly a tenth as massive, yield a clear correlation between the relative amount of intrahalo light in a system and the total mass of the system. This predicted correlation spans three orders of magnitude in mass from galactic scales (\( f_{\text{HIL}} \sim 1 - 5\% \) for \( M_{\text{host}} \sim 10^{12} M_{\odot} \)) to those of galaxy clusters (\( f_{\text{HIL}} \sim 10 - 40\% \) for \( M_{\text{host}} \sim 10^{15} M_{\odot} \)), and we refer the reader to Purcell et al. (2007) for a complete description of the method and prior results.

### 2.1 Intrahalo Light Model Update

An ingredient leading to the correlation between IHL fraction and host mass is the aforementioned variation of mass-to-light ratio (M/L) with halo mass, which is necessary in the prevailing structure formation model in order to reproduce empirical measurements of the galaxy luminosity function and clustering statistics (e.g., White & Rees 1978; Kauffmann et al. 1993; Somerville & Primack 1999; Tinker et al. 2003; Cooray & Milosavljević 2005). PBZ07 adopt the particular result of Yang et al. (2003), in which the authors constrain the conditional luminosity function (CLF) of galaxies in the Two-Degree Field Galaxy Redshift Survey (2dFGRS) and infer the characteristic B-band luminosity, \( L_c(M) \), for the brightest central galaxy sitting in a host halo of virial mass \( M \). In a new analysis by the same group, van den Bosch et al. (2007) investigate variation in their CLF results as a function of the cosmological parameters measured by WMAP
\(^{1}\) and introduce an updated theoretical model, which is integrated over the light-cone interval defined by the upper and lower redshift limits given by 2dFGRS data, and accounts for the scale-dependence of halo bias.

In Figure 1, we show the mass-to-light ratio derived by van den Bosch et al. (2007) and compare it to the previous CLF analysis of Yang et al. (2003), which was used in the fiducial model of PBZ07. In this paper, we update the model of Purcell et al. (2007) to reflect the more recent analysis of van den Bosch et al. (2007). The results of van den Bosch et al. (2007) indicate that in a WMAP1 cosmology galaxy formation occurs most efficiently in halos of host mass \( M \sim 10^{12.5} M_{\odot} \), where mass-to-light ratio is a minimum. Otherwise, \( M/L_c \) increases as a power-

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\(^{1}\) In this paper, we will refer to three cosmologies corresponding to WMAP data releases: WMAP1 with \( \Omega_m = 0.3 \) and \( \sigma_8 = 0.9 \), WMAP3 with \( \Omega_m = 0.23 \) and \( \sigma_8 = 0.74 \), and WMAP5 with \( \Omega_m = 0.258 \) and \( \sigma_8 = 0.796 \).
with cluster richness (e.g., Zibetti et al. 2005). In Figure 2 we present updated results for the relative fraction of luminosity in diffuse IHL compared to the total luminosity in the system, which includes the contributions from the brightest halo galaxy (BHG) in the center as well as destroyed (IHL) and surviving satellites (Sats), as a function of host halo mass. We predict a positive correlation between halo mass and IHL fraction spanning more than an order of magnitude in IHL fraction, with the dominant factor in the variation between this model and the result of PBZ07 being the updated slopes and minimum value in the behavior of $M/L_c(M_{\text{host}})$ as presented by van den Bosch et al. (2007). This prediction yields distributions of intrahalo light roughly consistent with galactic stellar halo luminosities, $f_{\text{IHL}} \lesssim 1 - 5\%$ for $M_{\text{host}} \lesssim 10^{12} M_\odot$, as well as intrachlor observations of diffuse light, $f_{\text{IHL}} \sim 10 - 40\%$ for $M_{\text{host}} \sim 10^{14} - 10^{15} M_\odot$.

### 2.2 Assigning Metallicities

Having predicted the relative amount of intrahalo stellar material in systems ranging in mass from dwarf galaxies up to rich galaxy clusters, we can also determine the expected chemical abundances in these diffuse components by considering the well-known correlation between luminosity and metallicity ($L-Z$ relation) in star-forming galaxies (e.g., Garnett & Shields 1987; Brodie & Huchra 1991). The $L-Z$ relation, which holds over ten magnitudes in optical luminosity (Zaritsky et al. 1994), is generally thought to be the result of an underlying correlation between stellar mass and metallicity for galaxies. These two properties are fundamental relics of galaxy formation and evolution, because they reflect the amount of gas tied up in a system’s stars and the efficiency of gas recycling and retention processes in that system, respectively.

Resolving the age-metallicity-reddening degeneracy for a particular stellar population translates a galaxy’s luminosity into stellar mass, $M_*$. The $M_* - Z$ correlation is ostensibly a consequence of the interplay between a host halo’s total baryonic mass and the effective yield of the system; larger galaxies being less susceptible (having higher stellar mass quotas) to outflow processes that decrease the quantities of metals present for subsequent generations of star formation (Tremonti et al. 2004).

Extensive surveys of star-forming galaxies have constrained the mass-metallicity relation at various redshifts. Using oxygen gas-phase abundances derived from optical nebular emission lines in galaxy data drawn from the Sloan Digital Sky Survey (SDSS), Tremonti et al. (2004) infer an $M_* - Z$ relationship for the local universe ($z \lesssim 0.1$), which is analytically well-fitted by a second-order polynomial in $\log(M_*)$. This trend applies for galaxies with stellar masses between $10^8 M_\odot \lesssim M_* \lesssim 10^{11.5} M_\odot$, and the work of Lee et al. (2009) extends the correlation into the low-mass regime ($10^8 M_\odot \lesssim M_* \lesssim 10^{10.5} M_\odot$) by measuring 4.5 µm luminosities for nearby dwarf irregular galaxies observed by near-infrared instrumentation aboard the Spitzer Space Telescope. For the mass range in which the two determinations overlap, the SDSS relation is roughly 0.3 dex more metal-rich than that derived for the dwarf-galaxy data, an offset that may be partially explained by two selection effects: SDSS fiber spectra preferentially sample the innermost

![Figure 3.](image-url) The fiducial, redshift-dependent mass-metallicity relation used to assign oxygen abundances to disrupted satellite galaxies produced by the model of PBZ07; in order to assess the chemical content of intrahalo light. Drawn from the model of Savaglio et al. (2005) and formulated explicitly in Equation 1, the *maroon* lines represent case 1 of the $M_* - Z$ relation at $z = 0$, 1, and 2 (solid lines of high, medium, and low thicknesses, respectively), and case 2 is plotted in orange dashed lines at the same redshifts, representing the original relation shifted by 0.3 dex towards lower metallicity, to reflect selection effects discussed in Erb et al. (2006). For comparison, we overplot with black squares data from the mass-metallicity relation at $z \sim 2$, as derived by Erb et al. (2006).
regions of spiral galaxies which may in actuality have radial metallicity gradients (e.g., Zaritsky et al. 1994), and oxygen abundances derived for SDSS data use bright-line estimation methods (in the absence of the temperature-sensitive [O III] emission line) which overestimate the true metallicity values by ~0.3 dex at roughly solar abundance and greater (e.g., Kennicutt et al. 2003; Bresolin et al. 2004).

There is evidence that the mass-metallicity relation has evolved with redshift. Specifically, galaxies with a given stellar mass at high redshift tend to have lower oxygen abundances than their local counterparts with the same stellar mass (Savaglio et al. 2005; Erb et al. 2006). Armed with a mass accretion history for disrupted subhalos, we can assign their stellar mass values using the adapted PBZ07 model and determine the appropriate oxygen abundance of the resultant IHL component by applying an $M_\star - Z$ relation that evolves with redshift to match each satellite's epoch of destruction. To accomplish this goal we adopt the prescription of Savaglio et al. (2005, hereafter S05), in which the authors investigate stellar mass and metallicity in galaxies at redshift $0.4 \leq z \leq 1.0$ from the Gemini Deep Deep Survey (GDDS) and Canada-France Redshift Survey (CFRS), in order to derive the form by which the $M_\star - Z$ relation changes as a function of cosmic time. This model translates the $M_\star - Z$ polynomial of Tremonti et al. (2004) into one consistent with their choice of stellar IMF and metallicity calibration, and extends the relation in redshift. It is worth noting here that we determine stellar metallicity via the time-dependent formulation describing oxygen gas-phase abundance, such that the chemical composition of our stars will reflect the metallicity of the gas from which they were formed, instead of the systematically richer gas-phase metallicity that would be measured at the present day.

To illustrate the importance of the selection-effect issues discussed above, we explore two mass-metallicity relations in our work. We present predictions for IHL metallicity based on each of these mass-metallicity relations. The two $M_\star - Z$ relations represent relatively high- and low-metallicities respectively and we expect that the predictions from these two relations bracket the true value. In case 1, we adopt the model of S05, and in case 2 we decrease the oxygen abundance by 0.3 dex across all stellar masses as motivated by the offset found in the analysis of Lee et al. (2006). For each destroyed satellite galaxy in our analytic formalism, we draw from a Gaussian distribution of metallicities centered on the mean $M_\star - Z$ relation and with a dispersion constant over host halo mass and equal to $\sigma = 0.2$ dex as derived by S05 for their sample of galaxies at $z \sim 0.7$. In Figure 3, we plot the fiducial mean mass-metallicity relation at $z = 0$, 1, and 2 for both cases. Throughout this work we adopt the standard units for oxygen metallicity in galaxies, $12 + \log(O/H)$ in which the solar abundance is 8.66 (Asplund et al. 2004). The functional form of our case 1 as drawn from S05 is for a given stellar mass $M_\star$ and Hubble time $t_H$:

$$12 + \log(O/H) = -7.59 + 2.5315 \log M_\star - 0.09649 \log^2 M_\star + 5.1733 \log t_H - 0.3944 \log^2 t_H - 0.403 \log t_H \log M_\star,$$

For this prescription, in order to reflect the buildup of both
stellar mass and the associated chemical composition of subhalo stars, we adopt the $t_{\text{H}}$ at which the satellite galaxy has formed half of the stellar mass it has at the time of accretion, i.e., the appropriate $M_*(t_{\text{H}}) = 0.5 M_*(t_{\text{acc}})$. As in PBZ07, we have assumed for simplicity that star formation is truncated upon the subhalo’s accretion onto the host halo, via processes of gas dynamics such as ram pressure stripping or strangulation.

Remnants of relatively recent accretion events will naturally be more metal-enriched than the diffuse light from ancient merger remnants, which give rise to a more spatially-uniform, nearly-virialized component of diffuse luminosity that should be more metal-poor than the tidal streams that are the coherent remnants of recent accretion events (Font et al. 2006). Our formalism defines subhalo disruption by mass loss alone and we do not trace the subsequent evolution of the liberated material in a self-consistent manner. Consequently, we must introduce additional modeling in order to distinguish bright tidal features from older relics of galaxy disruption. In their paper on the interpretation of diffuse streams as the result of satellite disruption around galaxies in a $\Lambda$CDM universe, Johnston et al. (2001) derive the form for the time evolution of a debris trail’s surface brightness, as a function of the progenitor satellite’s mass, the host halo mass, and the galactocentric radius of the satellite’s orbit. Their analysis is based on the destruction of satellites on circular orbits, but we utilize this approximate form in order to test the viability of separating the IHL metallicity along thresholds in dynamical age, which could be useful in studies of Local Group diffuse features such as the giant southern stream of M31, as we discuss in §3.

### 3 RESULTS

We make predictions for the oxygen metallicities of diffuse intrahalo stellar mass embedded in host halos with virial mass $10^{10.5} M_\odot \leq M_{\text{host}} \leq 10^{15} M_\odot$, as shown explicitly in Figure 3. In case 1, corresponding to the redshift-dependent $M_\star - Z$ relation obtained by SF05, our analysis predicts a mean $\langle O/H \rangle_{\text{IHL}}$ of $\sim -0.2 - 0.2$ with respect to the solar abundance, for diffuse intracluster luminosity present in halos with mass larger than $M_{\text{host}} \sim 10^{14} M_\odot$, while the case 2 metallicity is more sub-solar at those scales, $\langle O/H \rangle_{\text{IHL}} \sim -0.5 - 0.0$ as expected due to the difference between the normalizations of the two fiducial models. On galactic scales, we expect the abundance of the stellar halo to rise quickly as a function of host mass, increasing from $\langle O/H \rangle_{\text{IHL}} \sim -2$ to $\langle O/H \rangle_{\text{IHL}} \sim -1$ in the range $10^{11.5} M_\odot \leq M_{\text{host}} \leq 10^{12} M_\odot$. IHL metallicities in both cases evolve much more slowly in the regime of infalling and infalling light, the trend growing more shallow for host halos larger than $M_{\text{host}} \sim 10^{12.5}$ and rising weakly from $\langle O/H \rangle_{\text{IHL}} \sim -0.5$ to roughly solar metallicities, inducing a more distinct separation between case 1 and case 2, whose $\langle O/H \rangle_{\text{IHL}}$ distributions bracket the solar abundance on the largest scales investigated.

The distribution of IHL metallicity at fixed host mass is quite wide for stellar halos, with variance $\sigma_Z \sim 0.5$ dex at Galactic-mass scales, and is significantly more narrow for infalling and infalling light, where $\sigma_Z \sim 0.1$ dex and the average chemical abundance of diffuse stellar mass reaches a plateau. The normalization of this plateau varies non-trivially as we consider imposing thresholds in surface brightness, corresponding to the selection by dynamical age of destroyed satellite galaxies in order to distinguish the old,
for metal outflows due to the small variance they obtain in although Lee et al. (2006) endorse a more leisurely model becoming more efficient as the system’s host mass decreases, Kauffmann et al. 2004 regarding this threshold’s importance

One explanation for the origin of the mass-metallicity not every realization in this regime has had such an event. and thus becoming noisy at the galactic mass scale, since streams that remain brighter than than 12 mag/arcsec

subhalos whose tidal streams have dimmed to a B-band sur-

Figure 6. The difference between the metallicity of a host halo’s central galaxy, Z_{host}, and the metallicity of the intrahalo component, Z_{IHL}. For each case, the thick solid lines denote the mean of the distribution at fixed host mass, while the thin solid lines are contours bracketing 68% of each distribution. Shown with a diamond is the observed difference for the Milky Way, assuming a Galactic metallicity of [Fe/H] \sim \sim -0.7 \pm 0.1 solar, as determined by Ivezic et al. (2008), with an \alpha-enrichment of \sim 0.3 as suggested by Chang et al. (2002) yielding Z_{host} \sim 0.4 \pm 0.1. The stellar halo metallicity is taken to be Z_{IHL} \sim 1.1 as discussed in §4. The upper axis shows the central galaxy metallicities for each decade in host halo mass, as drawn from the fiducial M_{host} - M_* relation and the case 1 mass-metallicity model.

metal-poor intrahalo component from younger, brighter and more metal-rich stellar substructure currently undergoing disruption. In the left panel of Figure 3 we plot our case 1 IHL metallicity as a function of host mass for only those subhalos whose tidal streams have dimmed to a B-band surface brightness lower than \mu_B = 28 mag/arcsec^2, and in the center panel we show the same trend for diffuse features dimmer than \mu_B = 27 mag/arcsec^2. By contrast, the right panel excludes faint subhalo debris, selecting dynamically young streams that remain brighter than \mu_B = 27 mag/arcsec^2, and thus becoming noisy at the galactic mass scale, since not every realization in this regime has had such an event.

4 DISCUSSION

One explanation for the origin of the mass-metallicity relation for star-forming galaxies arises from galactic winds that induce a significant amount of metal-enhanced mass loss from galaxies with stellar mass below roughly $10^{10.5}$ (Tremonti et al. 2004, Gallazzi et al. 2005, see also Kauffmann et al. 2004) regarding this threshold’s importance for galaxy evolution in general, with the “blowout” process becoming more efficient as the system’s host mass decreases, although Lee et al. (2006) endorse a more leisurely model for metal outflows due to the small variance they obtain in the $M_* - Z$ relationship for dwarf irregular galaxies. Below the critical scale $M_{\text{crit}}^{*} \sim 10^{10.5} M_\odot$, the $M_* - Z$ correlation’s slope grows steeper with lookback time, supporting a galactic chemical evolution model predicating on longer e-folding times for star formation in lower-mass galaxies (Savaglio et al. 2003), a hypothesis consistent with the empirical phenomenon of cosmic “downsizing” in which more massive galaxies form the majority of their stars at a higher redshift than do less massive systems (Heavens et al. 2004; Juneau et al. 2003; Perez-Gonzalez et al. 2003).

Numerical hydrodynamical simulations of hierarchical structure formation have also generated a characteristic stellar mass $M_{\text{crit}}^{*} \sim 3 \times 10^{10} M_\odot$ which divides galaxy populations into two groups. The first contains large systems that formed most of their stars more than \sim 10 Gyr ago, having been assembled via mergers of stellar-dominated subhalos with little gas left over to produce a significant starburst during coalescence. The second group is composed of comparatively small systems that form stars more passively, allowing gas-rich mergers to produce enough star formation that the metallicity of the overall stellar content is affected by the significant fraction of new stars (see also Tissera et al. 2003). This stellar mass threshold remains constant to a redshift of $z \sim 3$, and $M_{\text{crit}}^{*}$ galaxies have roughly solar abundances that evolve very weakly over the same timeframe, these systems being typically embedded in halos of mass $M_{\text{host}} \sim 10^{12.5} M_\odot$ according to the formalism of van den Bosch et al. (2007). Convoluting this expectation with our prediction regarding the metallicity of diffuse intrahalo light produced by galaxy disruption, we note that both simulations (Stewart et al. 2008, and analytic models of galaxy formation (Porcelli et al. 2007) describe LCDM structure on all scales as being preferentially formed via mergers involving subhalos of mass $M \sim 0.1 M_{\text{host}}$, indicating that both accreted substructure and the diffuse intrahalo component should have roughly solar metallicities in halos of mass $M_{\text{host}} \sim 10^{13.5} M_\odot$. This context slightly favors our case 1 result, in which the mean metallicity of intragroup light on the relevant scale is very close to the solar oxygen abundance, although there is a scatter $\sigma \sim 0.15$ dex at fixed host mass in both cases.

Recent measurements of stellar halo metallicity in the Local Group seem to cluster around the point $Z_\odot \sim -1.5$ (Ferguson 2007, see also Kalirai et al. 2006 for a review of the halo abundance of M31). However, the alpha-enrichment of the Galactic halo is significant (observed at $+0.4$ as reviewed by McWilliam 1997), which is consistent with an intrahalo stellar population forming in an early burst, before type Ia supernovae could contribute much iron to the IGM (Matteucci 2003, see Venn et al. 2004 for a review of chemical signatures in hierarchical formation models). An appropriate observational benchmark for the stellar halo oxygen abundance is therefore $[O/H]_{IHL} \sim -1.1$ with respect to the solar metallicity, which falls along the lower 68% contour in case 1 of our fiducial theoretical result. For the Galactic disk’s iron abundance of $[Fe/H] \sim -0.7 \pm 0.1$ with respect to the solar metallicity (Ivezic et al., 2008, and an \alpha-enrichment of $+0.3$ as suggested by Chang et al. 2002), we also note that the difference between this $Z_{\text{host}} \sim -0.4 \pm 0.1$ and the IHL metallicity is $\sim 0.7$ dex. We show the expected behavior of the quantity $Z_{\text{host}} - Z_{\text{IHL}}$ as a function of host mass in Figure 4 and note that the Milky Way’s observed value slightly favors our case 1 model; fu-
ture abundance surveys of distant galaxies and diffuse light may provide further empirical constraints supporting the prediction that intracluster stars have similar metallicities to that of the cluster’s central galaxy, whereas intrahalo populations on smaller scales are significantly more metal-poor than their host galaxies.

The evolution of a galaxy’s metallicity arises from the equilibrating processes of the infall of gas and its subsequent enrichment in metals via star formation; these competing rates of dilution and enhancement are governed by the efficiency of gas accretion and processing. Recent theoretical investigations have reproduced observed metallicities in the intergalactic medium at $z > \sim 2$ and matched the $M_\star - Z$ relation’s slope and normalization by introducing a paradigm in which galactic wind velocities are proportional to the stellar velocity dispersion of the host system (the “momentum-driven” scenario of Finlator & Davé 2008) and the mass-loading factor $\eta$ of the outflow scales with a galaxy’s stellar mass as $\eta \propto M_\star^{1/3}$ at low masses and approaches unity at the blowout point, where winds begin to escape their host halo and the $M_\star - Z$ relation flattens to a roughly constant value. The steep rise in IHL abundance at and below the galactic scale occurs as intragalactic metal depletion processes dramatically fall to minimal efficiency with increasing host halo mass, thereby enriching satellite systems prior to disruption, and thus increasing the metallicity of the diffuse stellar component in higher-order structure as a similarly fast function of host mass. Given the rapidity of this trend, and the significant variance we obtain in the metallicities of stellar halos belonging to spiral-sized galaxies, we note that observational constraints on a possible correlation between IHL metallicity and host galaxy luminosity will likely reflect the stochastic and ongoing nature of the diffuse stellar component’s formation, as well as the particular mass accretion history of a given galaxy.

One such relationship is advocated by Mouhcine et al. (2005), in which stellar halo abundances are derived from color measurements of the red giant branch in off-disk fields and shown to increase with galactic luminosity across a wide range $-2 \lesssim Z \lesssim -0.5$, although Ferguson (2007) claims this correlation is non-existent when halo stars are kinematically selected. A more recent application of this method to an RGB-star survey of the Galaxy-analogue system NGC 891 has shown a broad IHL abundance distribution centered around $Z = -0.9$, more metal-rich by a factor of three than the stellar halos of both large Local Group galaxies (Mouhcine et al. 2007). We do predict a strong rise in halo metallicity as host mass increases through the galactic scale (shown in Figure 4), but the wide scatter at fixed mass suggests that the statistical accuracy of any such empirically-derived relation would be dramatically contaminated by variance in the individual mass assembly processes for each galaxy, as demonstrated by Figure 7 in which we obtain a power-law relationship between IHL abundance and the fraction of a system’s stellar mass contributed by the intrahalo component ($n \sim 0.95$ in $[O/H]_{\text{IHL}} \propto n \log f_{\text{IHL}}$), spanning the widest range at galactic scales and thereby suggesting that stellar halo metallicity more properly correlates

Figure 7. Case 1 $[O/H]_{\text{IHL}}$ as a function of IHL fraction for each realization at various fixed host masses.
with the luminosity of the stellar halo, and not necessarily the luminosity of the parent galaxy.

This correlation grows weaker when we consider increasingly more massive host halos, as the IHL metallicity distribution tightens and the IHL fraction flattens. We predict an $[O/H]_{	ext{III}}$ value of $\sim -0.5$ for weak groups such as the Local Group, which has a mass $M_{\text{host}} \sim 5.3 \times 10^{12} M_\odot$ according to Li & White (2008), although observational constraints in this regime remain elusive. On still larger scales, the Virgo cluster provides a more useful laboratory for the study of intrahalo stellar metallicity, although systematic errors in the photometry of RGB-tip stars in these fields cause great variance in the abundance values yielded (e.g., Durrell et al. 2002, in which the authors obtain $-0.8 \lesssim Z \lesssim -0.2$). In a recent study, Williams et al. (2007) identify $\sim 5300$ intracluster stars in Virgo, determining that 70% – 80% of them are older than $\sim 10$ Gyr and populated over a wide range in abundance ($-2.5 \lesssim Z \lesssim 0.0$), as we might expect from a diffuse population with multiple origins; the remaining 20% – 30% of the intrahalo population has a metallicity distribution function peaking near solar values, these younger stars having been more recently orphaned by disruption processes acting on their parent galaxy. Still more metal-rich is the intrahalo population of the cluster Abell 3888, which contains one component having formed at redshift $z > 1$ with high metallicity ($1 < Z \lesssim 2.5$), as well as a more centralized diffuse region at roughly solar abundance (Krick et al. 2008). The variation in our predicted distribution is of order $\sigma \sim 0.1$ dex, although the location of the plateau varies significantly with surface brightness cuts intended to separate older intrahalo populations from dynamically young IHL plumes in galaxy clusters. Typical measurements of intracluster light have analyzed fields without obvious luminous substructure, corresponding to the spheroidal halo of field stars in spiral galaxies. It appears that we must be careful about claims as to how much stellar mass actually lies in long-disrupted satellite remnants, as opposed to relatively bright diffuse tidal streams.

However, it is worth noting that stellar halo observations of galaxies outside the Local Group cannot distinguish stream-like substructure from background field stars, just as intragroup and intracluster studies cannot. Tidal features such as M31’s giant southern stream are rich in stellar mass (the progenitor may have been as bright as a billion solar luminosities according to Font et al. 2004) as well as metals ($Z \sim -0.5$ according to Guhathakurta et al. 2005), so we can reconcile our predictions with current galactic measurements given the caveat that typical halo metallicities reflect the underlying stellar component, without the inclusion of bright outer-halo substructure resulting from massive accretion events, a distinction made more clear by a recent semi-analytic treatment of baryon dynamics in numerical models of L$_*$-galaxy halos (Font et al. 2004, see also Bullock & Johnston 2005 for details of the simulation). We also predict a clear correlation between the oxygen abundance and the surface brightness of tidal streams in galaxy clusters, a prediction that will be testable as future deep surveys come online and metallicity distribution functions become more well-studied in diffuse intrahalo stellar populations at and above the galaxy scale.

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