SHREDDED GALAXIES AS THE SOURCE OF DIFFUSE INTRAHALO LIGHT ON VARYING SCALES

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Received 2007 February 28; accepted 2007 May 8

ABSTRACT

We make predictions for diffuse stellar mass fractions in dark matter halos from the scales of small spiral galaxies to those of large galaxy clusters. We use an extensively tested analytic model for subhalo infall and evolution and empirical constraints from galaxy survey data to set the stellar mass in each accreted subhalo, which is added to the diffuse light as subhalos become disrupted due to interactions within their hosts. We predict that the stellar mass fraction in diffuse, intrahalo light should rise on average from ~0.5% to ~20% from small galaxy halos (~10\(^11\) \(M_\odot\)) to poor groups (~10\(^13\) \(M_\odot\)). The trend with mass flattens considerably beyond the group scale, increasing weakly from a fraction of ~20% in poor galaxy clusters (~10\(^14\) \(M_\odot\)) to roughly ~30% in massive clusters (~10\(^15\) \(M_\odot\)). The mass-dependent diffuse light fraction is governed primarily by the empirical fact that the mass-to-light ratio in galaxy halos must vary as a function of halo mass. Galaxy halos have little diffuse light because they accrete most of their mass in small subhalos that themselves have high mass-to-light ratios; stellar halos around galaxies are built primarily from disrupted dwarf-irregular--type galaxies with \(M_\odot \sim 10^8 \ M_\odot\). The diffuse light in group and cluster halos is built from satellite galaxies that form stars efficiently; intrahalo light is dominated by material liberated from massive galaxies with \(M_\odot \sim 10^{11} \ M_\odot\). Our results are consistent with existing observations spanning the galaxy, group, and cluster scale; however, they can be tested more rigorously in future deep surveys.

Subject headings: cosmology: theory — galaxies: evolution — galaxies: formation

Online material: color figures

1. INTRODUCTION

When Zwicky first observed the diffuse, luminous component of the Coma cluster of galaxies, it was not clear what processes were responsible for it (Zwicky 1951). Today, the prevailing paradigm for structure formation is hierarchical; galaxies and clusters of galaxies of all sizes are built through sequential mergers of many smaller objects. Hierarchical structure formation theories provide a mechanism for the formation of intracluster light as material lost from shredded galaxies over the course of cluster formation (Gallagher & Ostriker 1972; Merritt 1983; Byrd & Valtonen 1990; Babul et al. 2003; Gnedin 2003; Mihos 2004; Murante et al. 2004; Lin & Mohr 2004; Willman et al. 2004; Sommer-Larsen 2006; Rudick et al. 2007; Conroy et al. 2007). Whereas the building blocks of clusters are galaxies, galaxy-sized objects build their masses by acquiring relatively low-luminosity (dwarf) galaxies, which may subsequently be destroyed by tides and heating processes to produce the diffuse, stellar halos around galaxies like the Milky Way (Scarbrough & Zinn 1978; Johnston et al. 1996, 2001; Johnston 1998; Bullock et al. 2001b; Bullock & Johnston 2005; Robertson et al. 2005; Diemand et al. 2005; Read et al. 2006; Font et al. 2006; Abadi et al. 2006). Whether in clusters or galaxies, we refer to this diffuse material as “intrahalo light” (IHL) and adopt the symbol \(f_{\text{IHL}}\) to express the fraction of the total system luminosity found in this diffuse component. In this paper we explore the connection between the size of a system and the relative fraction of its total light contributed by intrahalo stellar material. In particular, we predict the mean and variance in the IHL fraction as a function of dark matter halo mass, and we explore the origin of the scatter in IHL at fixed halo mass.

Most of our knowledge about the IHL on galaxy scales (~10\(^11\) – 10\(^12\) \(M_\odot\)) comes from star counts within the Local Group. The stellar halo of the Milky Way contains \(f_{\text{IHL}} \sim 1\%\) of the Galaxy’s total luminosity (Morrison 1993; Wetterer & McGraw 1996; Morrison et al. 2000; Chiba & Beers 2000; Yanny et al. 2000; Ivezić et al. 2000; Siegel et al. 2002). This number can be as large as \(f_{\text{IHL}} \sim 2\%\) if the unbound Sagittarius stream stars are included in the diffuse component (e.g., Law et al. 2005).

Interestingly, while the dark halo of M31 is thought to be roughly the same size as that of the Milky Way (\(M_{\text{M31}} \sim 10^{12} \ M_\odot\); see Klypin et al. 2002; Seigar et al. 2006), the recently discovered, metal-poor stellar halo of M31 may contain a significantly higher fraction of that galaxy’s light, \(f_{\text{IHL}} \sim 2.5\%–5\%\) (Irwin et al. 2005; Guhathakurta et al. 2005; Kalirai et al. 2006; Chapman et al. 2006). If the great Andromeda stream (Ibata et al. 2001) were included as diffuse light, this count would be larger. These observations immediately suggest that there should be a substantial spread in IHL components among galaxy-sized systems. Detections of a stellar halo component in the smaller disk galaxy M33 (\(M_{\text{M33}} \sim 10^{11} \ M_\odot\)) have recently been reported (Hood et al. 2007; McConnachie et al. 2006). These estimates are consistent with a very low stellar mass fraction in the M33 halo, \(f_{\text{IHL}} \lesssim 1\%\), although a higher number is not ruled out (A. Ferguson 2007, private communication).

In more distant galaxy halos, the IHL is both harder to detect and more difficult to discriminate from other extended components (e.g., Dalcanton & Bernstein 2002). Some results suggest that galactic stellar halos with \(f_{\text{IHL}} \sim 1\%–5\%\) are not uncommon (Sackett et al. 1994; Morrison et al. 1997; Weil et al. 1997; Lequeux et al. 1998; Abe et al. 1999; Zibetti & Ferguson 2004). Recent work by S. Buehler et al. (2007, in preparation) regarding the edge-on galaxy NGC 4244 indicates the existence of an asymmetric stellar component far above the system’s exponential thin...
disk, although nondetections are also reported in galaxies of similar size (e.g., Zheng et al. 1999; Fry et al. 1999). Of particular interest is the case of NGC 300, a low-luminosity, late-type galaxy in which no stellar halo has yet been detected, despite the successful identification of an exponential disk that extends over 10 scale lengths from the disk’s center (Bland-Hawthorn et al. 2005). Of course, the differences from object to object may reflect systematic observational issues, but taken at face value, they indicate that the IHL fraction around galaxy halos shows significant variation and that there may be a trend for low \( f_{\text{IHL}} \) levels in small galaxies. Relevant determinations will become more precise as resolved-star surveys extend beyond the Local Group (e.g., de Jong et al. 2007).

Diffuse light fractions on group scales \((M_{\text{vir}} \sim 10^{13} \, M_\odot)\) also exhibit considerable variation from system to system; however, the IHL component typically accounts for a more substantial fraction of the total luminosity of the system than it does on galaxy scales. Observations suggest that the M81 and Leo groups have at most a few percent of their light in diffuse form (Feldmeier 2006; Castro-Rodríguez et al. 2003). At the opposite extreme, HGC 90 has a reported IHL fraction of \( f_{\text{IHL}} \sim 45\% \) (White et al. 2003). Studies in other groups of roughly the same size yield a range of IHL fractions, \( f_{\text{IHL}} \sim 5\% - 30\% \) (Da Rocha & Mendes de Oliveira 2005; Aguerri et al. 2007).

Galaxy clusters \((\sim 10^{14} - 10^{15} \, M_\odot)\) typically show the highest fractions of diffuse light. Again the scatter in estimated values is significant but \( f_{\text{IHL}} \) values range from \( \sim 10\% \) to \( 40\% \) (Thuan & Kormendy 1977; Melnick et al. 1977; Uson et al. 1991; Bernstein et al. 1995; Calcâneo-Roldáñ et al. 2000; Lin & Mohr 2004; Feldmeier et al. 2004a; Mihos et al. 2005; Zibetti et al. 2005; Krick et al. 2006; Seigar et al. 2007). A review by Ciardullo et al. (2004) describes recent surveys in the small Fornax and Virgo clusters and points out a distinctive falloff in the IHL fraction for systems smaller than \( L \sim 10^{11} L_\odot \) quite similar to the break we see in our predicted fractions below. Another interesting, although tentative, trend is that IHL fractions in clusters without cD galaxies appear to have a somewhat smaller typical \( f_{\text{IHL}}(\sim 10\% - 20\%) \), than do clusters with cD galaxies (Feldmeier et al. 2004a, 2004b).

Recently, a series of papers by Gonzalez et al. (2005, 2007) have argued that a more appropriate quantity to investigate is the sum of the diffuse intracluster light with that of the brightest cluster galaxy (more generally, the “brightest halo galaxy,” or BHG) since it is difficult to disentangle the two components (the same approach is advocated by Comray et al. 2007). Gonzalez et al. (2005) find that the sum of IHL + BHG light is dominated by the diffuse component on cluster scales, IHL/(IHL + BHG) \( \sim 80\% \). Moreover, Gonzalez et al. (2007) find that, compared to the total light in the cluster, the IHL + BHG fraction decreases from \( \sim 35\% \) in low-mass clusters \( M \sim 10^{14} \, M_\odot \), to \( \sim 25\% \) in more massive clusters. As we discuss below, these trends are very much in line with our expectations.

Comparing predictions for the IHL fraction with observational data is a nontrivial task. On the galaxy scale, total stellar halo luminosities depend sensitively on the difficult-to-measure central core radius assigned to the faint halo component. In addition, the IHL will typically have a different color than the bound light in galaxies (because it likely traces different star formation epochs), implying that the IHL fraction should generally be a function of the luminosity band or tracer populations used to determine it. Moreover, some traditional determinations of intracluster light have used relatively small patches of sky within the clusters themselves, introducing a statistical shot-noise error term into the inferred IHL values. The deep imaging necessary for intracluster observations is also heavily dependent on sky subtraction, providing another systematic barrier to precision IHL measurements on these scales. Ideally, direct comparisons between predictions and observations will mimic the influence of particular observational techniques and choices on theoretical predictions. The goal of such studies would be to produce predictions and observational results that can be compared in their detail (e.g., Rudick et al. 2007; Sommer-Larsen 2006).

In this paper our aim is not to make such detailed comparisons between predictions and observations. Rather, we focus on predicting the general behavior of IHL fractions as a function of the size of the system from dwarf galaxies to large clusters.\(^4\) We also explore the typical galaxy size that contributes to IHL as a function of halo mass and explore the scatter from system to system at fixed host mass. The scope of this study represents a challenge for direct numerical simulation of halo formation due to the limited dynamic range of such computations. To achieve our goals, we rely on an analytic treatment of halo formation (Zentner et al. 2005; see below). We normalize the stellar content of our accreting halos to match empirical constraints from \( z \sim 0 \) observations (Yang et al. 2003; Vale & Ostriker 2004; Bell & de Jong 2001; de Jong & Bell 2006). We make the explicit assumption that stellar material in galaxies is liberated when their dark matter halos become significantly stripped. We make no distinction between material that has recently been liberated by tidal interactions (which may therefore appear as streamlike structure) and the general diffuse background. In order to avoid any ambiguities associated with the evolution of luminosity in different components, we quote the diffuse stellar mass fraction, \( f_{\text{IHL}} \equiv M_{\text{diff}}/M_{\text{total}} \).

In the next section we outline our two-step model for IHL predictions. In § 3 we briefly describe a toy model for the scaling of the IHL fraction with halo mass that serves both to frame our expectations for the fiducial result and to demonstrate the generality of this scaling. In § 4 we present our results for IHL fractions, reserving § 5 for discussion and review. Throughout this work we adopt a \( \Lambda \) Cold Dark Matter cosmology model with \( h = 0.7, \Omega_m = 1 - \Omega_\Lambda = 0.3, \) and a primordial power spectrum that is scale-invariant, \( n = 1, \) and normalized to \( \sigma_8 \sim 0.9 \).

\section{METHODS}

\subsection{Dark Halo Accretion and Disruption}

We model host dark matter halo mass accretion histories and track the evolution of accreted dark matter subhalos using an analytic prescription developed and tested against dissipationless cosmological simulations by Zentner et al. (2005, hereafter Z05). This approach is based on the earlier model of Zentner & Bullock (2003). The analytic technique enables us to explore quickly the expected variety of accretion and disruption histories for host halos at a series of different masses. The model has proven remarkably successful at reproducing subhalo count statistics, radial distributions, and two-point clustering statistics measured in full, high-resolution \( N \)-body simulations in regimes where the two techniques are commensurable. This success spans more than 3 orders of magnitude in host halo mass and persists as a function of redshift (Z05). The range over which this agreement is known to exist is limited only by the dynamic range of the simulations used by Z05. In what follows, we apply the analytic model outside the range over which it is well tested, but we know of no

\(^4\) Note that Murante et al. (2004) predicted a positive trend between intracluster light fraction and cluster mass, focusing only on cluster scales. We extend the range of mass by more than 2 orders of magnitude.
reason that it should fail outside of this range. Of course, more precise estimates that involve full N-body and hydrodynamical simulations will need to be made to refine our predictions; however, the general success of the model suggests that our predictions should be accurate enough that the approximate dynamical treatment of subhalos is not the limiting source of error and that potential differences are likely to test our assumptions about the evolution of stellar mass. Even so, many of the qualitative trends we derive are reflections of very general features of hierarchical structure formation and should be robust. Here we provide a brief overview of the technique and refer the reader to Zentner et al. (2005) and the similar models of Taylor & Babul (2004), Peñarrubia & Benson (2005), Faltenbacher & Mathews (2005), and van den Bosch et al. (2005) for more detail.

In hierarchical cosmologies such as ΛCDM, dark halos accumulate their mass through a series of mergers with smaller objects. The first step in our model is to select a host halo mass $M_{\text{host}}$ at $z = 0$ and generate a subhalo-based mass accretion history using the extended Press-Schechter formalism (Bond et al. 1991; Lacey & Cole 1993; for a recent review see Zentner 2006). We use the particular implementation advocated by Somerville & Kolatt (1999). The merger tree contains a list of all of the merger times and masses of all of the smaller halos that have merged to form the final object. Every time there is a merger, the smaller object becomes a subhalo of the larger object. This is a Monte Carlo procedure. Each merger event is drawn from a probability distribution and by realizing merger trees for numerous halos of the same final mass, we can probe the variety of formation histories that lead to final objects of the same size. As we discuss below, this variety of halo mass acquisition histories is a primary source of scatter in the fraction of IHL at fixed host mass.

After constructing a large number of merger histories at each final mass scale, we then track the evolution of subhalos in the dense environments of their host systems. Specifically, we assign an initial orbital energy and impact parameter to each merging subhalo. These values are chosen from probability distributions extracted from cosmological N-body simulations in Z05. We then integrate the orbit of each subhalo in the potential of the main halo from the time of accretion to the epoch of observation. We model tidal mass loss using a modified tidal approximation and a prescription for internal heating, as well as the effect of dynamical friction using an adaptation of the Chandrasekhar formula (Chandrasekhar 1943) suggested by Hashimoto et al. (2003). For simplicity, we model the density structures of all halos and subhalos by the spherically symmetric density profile of Navarro et al. (1997), NFW. For each halo and each subhalo, we set the concentration of the NFW profile according to the prescription of Wechsler et al. (2002) to account for the correlation between mass accretion history and halo concentration. Masses are defined relative to the virial overdensity $\Delta_{\text{vir}}$, where $\Delta_{\text{vir}} = 337$ at $z = 0$ (e.g., Bullock et al. 2001a).

Each subhalo has a well-defined rotation curve, $V_c = \sqrt{GM(<r)/r}$, that peaks at a velocity $V_{\text{max}}$. As the subhalo orbits within its host, it gradually loses mass at all radii and the value of $V_{\text{max}}$ declines. A subhalo is declared to be “disrupted” when its maximum circular velocity falls below $V_{\text{crit}} = f_{\text{crit}}V_{\text{max}}(f_{\text{face}})$. The quantity $f_{\text{crit}}$ is a parameter that allows us to determine when the galaxy associated with each halo will contribute its stars to the diffuse light of its host halo. We have some freedom to tune $f_{\text{crit}}$ to match empirical constraints on the number of surviving satellite galaxies per halo (see, e.g., Yang et al. 2003 and discussions below). We expect that a satellite galaxy will typically remain bound within its subhalo until the subhalo loses a significant portion of its mass. Physically, $f_{\text{crit}}$ should not be so high that a system would be classified as disrupted when its host halo is only slightly less massive than it was at accretion. Similarly, a very low choice of $f_{\text{crit}}$ would ensure that the galaxy would not be considered destroyed until the dark matter in its host subhalo is less massive than the galaxy itself.

Adopting a simple mass-scaling argument may allow us to gain physical insight into the disruption threshold, if we consider that the virial mass of a halo scales approximately as $M \propto V_{\text{max}}^{3.4}$ (Bullock et al. 2001a). With this in mind, an $f_{\text{crit}}$ value of 0.8 translates to the halo being “disrupted” when it has lost just over half its mass, while $f_{\text{crit}} = 0.2$ implies a mass-loss threshold of more than 99.5%. Clearly, the smaller our $f_{\text{crit}}$ is, the more assured we can be that galaxies meeting the criterion are truly dispersed, but if this parameter is chosen to be too small, then we may falsely associate galaxies with what should rightly be diffuse, luminous material. As discussed below, we adopt $f_{\text{crit}} = 0.6$ as our fiducial value primarily because it produces reasonable agreement with empirical constraints described in § 2.2. This choice implies disruption begins to occur when just under ~20% of the halo mass remains bound.

Our definition of “disruption” is not necessarily meant to indicate that beyond this threshold, a subhalo must become physically unbound due to the interaction within the host potential. Rather, our intention is to introduce some effective criteria whereby it would be sensible to assign a large fraction of the subhalo’s stellar mass to a diffuse component. The parameter $f_{\text{crit}}$ denotes this transition from a bound galaxy component that contributes little diffuse light, to a tenuous structure that relinquishes most of its stellar mass to the diffuse component of the host halo. In our IHL predictions, we make the explicit assumption that the stars initially assigned to a subhalo become “diffuse” when that subhalo is “disrupted” according to the aforementioned criterion.

Armed with a prescription for the mass accretion histories of halos and the subsequent orbital dynamics of their satellites, we can investigate the predicted substructure distributions and overall accretion histories for host halos of various masses. Our main results rely on 1000 realizations for virial host masses from $10^{10.5}$ to $10^{15} M_\odot$, with four discrete intervals in each decade (e.g., in log space: 11.2, 11.5, 11.8, 12.0, etc.), for a total of 19 mass bins. The solid lines in Figure 1 show the fraction of host halo mass accreted in satellite halos of a given mass $(dN/\text{d} \log M_{\text{sat}})$ averaged over 1000 realizations for host halos of mass $M_{\text{host}} = 10^{13} M_\odot$ (top left) through $M_{\text{host}} = 10^{15} M_\odot$ (bottom left) at $z = 0$. To be explicit, $f(>M_{\text{sat}})$ is the cumulative mass fraction in satellites larger than $M_{\text{sat}}$ and our prescription demands that $f(>M_{\text{sat}}) \rightarrow 1$ as $M_{\text{sat}} \rightarrow 0$ (i.e., all of a halo’s mass is accreted in subhalos of some size). In each panel, the dot-dashed lines include only subhalos that survive to the present day and the dashed lines include only subhalos that are disrupted, according to the above definition, between the epoch of accretion and $z = 0$.

It is important to note that regardless of host mass, the majority of mass is accreted in subhalos of mass $M_{\text{sat}} \sim 0.05$–0.1$M_{\text{host}}$. In addition, surviving subhalos contribute much less mass than their destroyed counterparts of similar size in galactic systems, while their relative contributions are more even in cluster-size halos. This trend arises because high-mass halos accrete their subhalos more recently than low-mass halos. Therefore, the subhalos of low-mass halos are typically more dynamically evolved and more likely to be destroyed (see Z05). These facts are fundamental to understanding the diffuse light fractions as a function of host mass, the consequences of which we explore in § 3.
2.2. Assigning Light to Dark Matter Halos

We assign a luminous component to each accreted halo using an empirical model that is normalized to $z = 0$ galaxy constraints. We assume that every accreted subhalo and every host halo contains a central galaxy. For every system accreted at time $t_{\text{acc}}$ we determine the stellar mass that this system would have today (at $t = t_0$ or $z = 0$) according to empirical mass-to-light ratios. Next, we extrapolate this $z = 0$ value backward in time to obtain $M_*(t = t_{\text{acc}})$ using an empirically motivated star formation law. The $z = 0$ normalization guarantees that our model produces the required relationship between host halo mass and (central) galaxy luminosity required to match local galaxy counts and galaxy clustering observations.

As we show below, our results for IHL fractions are quite insensitive to star formation assumptions. Indeed, our primary prediction, that the IHL fraction in halos will vary strongly with mass scale, is extremely robust, and is driven by the empirical fact that the global mass-to-light ratio $(M/L)$ in $\Lambda$CDM halos must vary strongly with host halo mass in order to reproduce the observed galaxy luminosity function and clustering statistics (e.g., White & Rees 1978; Kauffmann et al. 1993; Somerville & Primack 1999; Tinker et al. 2005; Cooray & Milosavljević 2005).

We adopt the $M/L$ relation inferred by Yang et al. (2003) in their model “M1.” Yang et al. (2003) used data from the Two-Degree Field Galaxy Redshift Survey (2dFGRS) to constrain the “conditional luminosity function” (CLF) of the 2dFGRS galaxies. This comparison allowed them to derive a characteristic $B$-band luminosity, $L_c(M)$, for the central (brightest) galaxies that sit in halos of virial mass $M$ (for related analyses, see van den Bosch et al. 2003; Tinker et al. 2005; Cooray & Milosavljević 2005; Yang et al. 2005). The solid line in Figure 2 shows the inferred total mass-to-light ratio $(M/L_c)$ as a function of halo mass. The dotted line shows an independent result from Vale & Ostriker (2004), which we utilize below in order to investigate the dependence of our conclusions on the specific choice of $(M/L_c)$ function. Note that in both cases, galaxy formation is most efficient in dark halos of virial mass $M \approx 5 \times 10^{11} M_\odot$ and the conversion of baryons to stars is increasingly less efficient as we consider halos with masses either larger or smaller than this scale.

In practice, we work with stellar mass rather than luminosity to avoid uncertainties associated with stellar population evolution. After computing the central galaxy luminosity using the Yang et al. relation shown in Figure 2, we convert this luminosity to...
to a stellar mass using the average “mass-dependent dust” relation from Bell & de Jong (2001):

$$M_*^0 = 0.75 \left( \frac{L_c}{10^{10} L_\odot} \right)^{0.33} .$$

(1)

We have adjusted the Bell & de Jong (2001) normalization down by a factor of 1.26 as advocated by their more recent work (de Jong & Bell 2006). In the final analysis, our predictions for diffuse light fractions depend very little on the overall normalization.

If we were interested only in contemporary galaxy and halo properties, the $M/L_c$ relation at $z = 0$ would suffice. However, the majority of the subhalos in our models are accreted well before $z = 0$. This fact forces us to adopt a star formation prescription in order to extrapolate our $z = 0$ stellar masses to earlier times. For simplicity, we assume that a galaxy’s star formation is truncated at the time it is accreted into a larger host, perhaps due to ram pressure stripping or the fact that gas leaks more readily out of the potential well of a subhalo located in a background host than it would if the satellite were left alone in the intergalactic field.

After setting the $z = 0$ stellar mass, we adopt a simple approach that models star formation with minimal parameterization, in order to estimate the stellar mass that a particular system would have had at the time of accretion, $t_{\text{acc}} < t_0 \approx 13.6$ Gyr. We impose a history

$$M_* (t) = M_* (t_0) \left[ 1 - \left( \frac{t_0 - t}{t_0} \right)^\alpha \right] .$$

(2)

This equation introduces a second free parameter $\alpha$ into our analysis, which can be adjusted to produce a wide range of evolutions for the stellar mass in a system. For example, $\alpha = 0.25$ will cause a galaxy to form most of its stellar component within the last 2 Gyr, while a larger value of $\alpha = 2$ results in a system with a much earlier formation epoch, increasing the look-back time to half-stellar-mass formation by roughly a factor of 5. As in our choice of $f_{\text{en}} = 0.6$ for the disruption parameter, we similarly adopt $\alpha = 1$ to best match the expected luminosity function of satellite galaxies in host halos of a given mass from Yang et al. (2003). We make these choices primarily for convenience and concreteness, and we demonstrate in § 4.3 that our main results for IHL fractions are largely insensitive to these parameter choices.

An example of our (surviving) galaxy population is described by the cumulative luminosity function plotted in Figure 3. We caution that this figure, unlike our main results below, focuses on galaxy luminosity rather than stellar mass. While we allow for stellar mass buildup with time, we do not include any luminosity evolution, which should be important for determining the B-band luminosity of cluster galaxies. We would expect, for example, that systems that have survived in the cluster environment for several Gyr would have stopped forming stars and faded in blue light. Instead, we have used equation (1) to convert between stellar mass and luminosity regardless of the redshift at which the satellite was accreted. We neglect any explicit stellar population modeling in order to keep our methods as simple as possible and to concentrate on robust, model-independent predictions. We present this only to demonstrate the gross consistency with inferred satellite galaxy populations in halos and do not adopt this strategy for any of our predictions below.

The solid line in Figure 3 shows the cumulative number of surviving galaxies (including the central galaxy) in a cluster-sized host halo, $M_{\text{host}} = 10^{14.5} M_\odot$, as a function of galaxy luminosity. The dashed line shows the empirically derived CLF result of Yang et al. (2003). Here, and for the rest of the paper unless otherwise stated, we have used our fiducial parameter choices $f_{\text{en}} = 0.6$ and $\alpha = 1$. Overall, the agreement is encouraging, and we find similar results for host halos of various masses. We match the empirical expectation quite well for the brightest galaxies, which is not surprising because the central galaxy is forced to be of the “correct” luminosity by construction. We gradually begin to overpredict satellite galaxy counts relative to the empirical line at faint luminosities, but as we now argue, this is not of serious concern for a number of reasons. First, as we show below, the vast majority

![Figure 2](image.png)

**Fig. 2.—** Total mass-to-central-galaxy-light ratio as a function of halo mass. The solid curve is the value inferred by Yang et al. (2003). This represents the $L_c(M)$ relation that we adopt in our fiducial models. For comparison, the dotted line is the mass-to-light ratio presented by Vale & Ostriker (2004).

![Figure 3](image.png)

**Fig. 3.—** Cumulative number of surviving galaxies as a function of luminosity, both in our fiducial model (solid line) and in the Yang et al. CLF analysis (dashed line), for a host halo of mass $M_{\text{host}} = 10^{14.5} M_\odot$. The model line represents the mean of 1000 fiducial realizations, and the error bars representing the error on the mean over the sample are smaller than the model line’s thickness on this plot.
of accreted stellar mass will be contributed by the most massive accreted galaxies. This suggests that an accurate reproduction of the brightest satellites is the most important aspect of the IHL calculation. Second, the faintest galaxies will likely be most affected by luminosity evolution (which we do not include). These objects tend to survive the tug of dynamical friction longer than their more massive companions, and we expect them to fade considerably in $B$-band light as they evolve in the cluster environment. Finally, although errors in the derived luminosity function are not explicitly discussed in Yang et al. (2003) the faintest galaxies in clusters are certainly weakly constrained by gross galaxy statistics because they are only a minor contributor to the global count of faint galaxies in the universe (see, e.g., the cluster luminosity functions in Yang et al. 2005).

2.3. Evolving the Diffuse Stellar Mass and the Central Galaxy Stellar Mass

To calculate the amount of diffuse light in a cluster, group, or galaxy halo, it is necessary to determine whether the stellar material from a disrupted halo should be included as extended, diffuse material or as material that is incorporated into the central galaxy. In practice, infalling satellites should deposit stellar mass into both the central galaxy and the diffuse component. However, modeling these interactions in detail is challenging, so it is difficult to budget the fraction of the infalling stellar material that should be assigned to the diffuse component and the fraction that should be assigned to the central galaxy.

To circumvent this complication, we employ two simple, alternative models for adding stellar mass to the central galaxy and diffuse components that should bracket the outcome from a full modeling of the baryonic components. In case 1 we classify all stellar material from disrupted subhalos as IHL. In this case, the diffuse stellar mass fractions should be maximized. In case 2 we exclude from the IHL all galax stars from subhalos that make an approach closer than a radius $r_c(M^\text{host})$ to the center of their host halos. In these instances, we add the libered stars to the stellar mass of the central object. Relative to case 1, stellar mass is removed from the diffuse component and added to the light of the central galaxy. This causes diffuse stellar mass fractions to be smaller in this case. We associate $r_c$ with a characteristic outer radius for the central galaxy. To be conservative, we adopt a fairly large outer radius $r_c = 10$ kpc, for central galaxies of stellar mass $M_\text{c} = 4 \times 10^{10} M_\odot$. We assume that $r_c$ scales according to the findings of Shen et al. (2003) for Petrosian half-light radii of galaxies in the Sloan Digital Sky Survey. To be explicit, we use $r_c \propto M_\ast^{0.4}$ for $M_\ast > M_\ast^\text{crit}$ and $r_c \propto M_\ast^{0.16}$ otherwise. The generous value of $r_c$, along with the assumption that all stellar mass is assigned to the central galaxy and that none of the stellar mass goes into the diffuse component, should lead to minimal IHL fractions in case 2.

Thus far, we have only considered the disruption of subhalos belonging to the trunk level of the host halo’s merger tree, i.e., we have not made any determinations about the diffuse stellar content already present in accreting subhalos, often referred to as “preprocessed” intrahalo light (see, e.g., Rudick et al. 2007). We do not expect galactic-scale host halos to carry much of this preprocessed stellar material, since accreting dwarf satellite galaxies typically have very little of their luminosity in diffuse form, but cluster-sized hosts accrete most of their mass in galaxy groups that may have a significant amount of IHL already present. In order to replicate this phenomenon, we first obtain our fiducial result (without the presence of preprocessed IHL), which is then used to interpolate an initial IHL value for each accreting subhalo. We then reproduce the fiducial IHL fraction, this time including diffuse stellar mass already present in subhalos and contributing that amount to the host’s total IHL on the subhalo’s accretion, essentially bootstrapping case 1 into itself in order to account for preprocessed intrhalo luminosity. We expect this model to differentiate itself from the initial result on large-mass scales, at which subhalos are likely to have diffuse stellar components that contribute a nonnegligible portion of the total subhalo luminosity. It is also worth noting that this second-order substructure is likely to carry increasingly less IHL than the fiducial model predicts at fixed mass because these subhalos will be younger and less luminous and will be less dynamically evolved so less luminosity could have been converted to diffuse luminosity. This indicates that our preprocessing method will slightly overestimate the contribution to the total host IHL made by diffuse stellar mass belonging to higher-order subhalos.

3. A TOY MODEL FOR THE INTRAHALO LIGHT FRACTION

Before proceeding, we derive a crude, analytic estimate for the scaling of the IHL fraction as a function of host halo mass. This model serves to frame our expectations for the general behavior of IHL fraction with mass, to highlight the features of hierarchical structure formation models most relevant to the determination of IHL fractions as a function of halo mass, and to demonstrate the generality of the halo mass-IHL fraction trends that we present in more detail in the following section.

The gross scaling of IHL fraction with halo mass can be understood from two robust, cosmologically motivated inputs:

1. Host halos of mass $M$ tend to accrete most of their mass in subhalos of mass $M_{\text{sat}} \sim 0.05 M_{\text{host}}^{-0.1} M_{\text{host}}$ (Fig. 1), and these halos are disrupted very efficiently due to dynamical friction.
2. Galaxy formation picks out a typical halo mass $M_g \approx 5 \times 10^{11} M_\odot$, where star formation is most efficient, and the efficiency of star formation declines rapidly away from this value (Fig. 2).

To begin with, it is useful to introduce an approximate analytic fit to the adopted $(M/L)_c$ relation from Yang et al. (2003):

$$\frac{M}{L_c(M)} \approx 50 \left(\frac{M}{M_\ast}\right)^{-3/4} \left[1 + \left(\frac{M}{M_\ast}\right)^{3/2}\right].$$

The differential contribution to the IHL fraction from a satellite of mass $M_{\text{sat}}$ can be computed by introducing two parameters: $f_{\text{destroy}}$, which encapsulates the probability that this satellite will be destroyed, and $f_{\text{diff}}$, which describes the fraction of the satellite’s stellar mass that contributes to the diffuse light once it is destroyed. Conceptually, this decomposition is useful, because $f_{\text{destroy}}$ has a known dependence on host and satellite halo masses (Z05; see Fig. 1). We will show that this dependence is subdominant, so for our purposes we can condense these into a single parameter, $f_d = f_{\text{destroy}} f_{\text{diff}}$, that accounts for the average fraction of its total stellar mass that a satellite contributes to the IHL. As we stated above, the mass dependence of $f_{\text{destroy}}$ is weak and is not the dominant factor that gives rise to the mass scaling of the IHL fraction, and for simplicity we will assume the composite parameter $f_d$ to be a slowly-varying function of mass.

The differential contribution to the IHL fraction from satellite halos in the mass range $dM_{\text{sat}}$ around $M_{\text{sat}}$ is then

$$\frac{dI_{\text{HL}}}{dM_{\text{sat}}} = f_d \frac{L(M_{\text{sat}})}{L(M_{\text{host}})} \frac{dn_{\text{acc}}}{dM_{\text{sat}}}$$

$$\sim f_d \left(\frac{M_{\text{sat}}}{M_{\text{host}}}\right)^{3/4} \frac{1 + (M_{\text{host}}/M_\ast)^{3/2} dn_{\text{acc}}}{1 + (M_{\text{sat}}/M_\ast)^{3/2}},$$
where $\frac{dn_{\text{acc}}}{dM_{\text{sat}}}$ is the mass function of accreted satellites. In general, the amount of total and stellar mass accreted into the system is dominated by the few most massive satellites near $\sim M_{\text{host}}/20$ (see Fig. 1). As a final rough approximation, we assume that satellites of this mass dominate the integral over $M_{\text{sat}}$. This gives

$$f_{\text{IHL}}(M) \sim f_{\text{d}} n_{\text{eff}} \frac{L(M_{\text{host}}/20)}{L(M_{\text{host}})} \sim 0.005 f_{\text{d}} n_{\text{eff}} \left[ \frac{1 + (M_{\text{host}}/M)^{3/2}}{1 + (M_{\text{host}}/20M)^{3/2}} \right],$$

where we have introduced a final parameter $n_{\text{eff}}$, which represents an effective number of satellites near mass $M_{\text{sat}} = M_{\text{host}}/20$ and will be of order unity (Fig. 1), and $f_{\text{d}}$ is understood to be evaluated near $M_{\text{sat}} = M_{\text{host}}/20$.

As will be clear in the following section, this extremely simple model captures the general features of our more detailed predictions. In our full model, $f_{\text{d}}$ should be less than 1 and $n_{\text{eff}}$ should be of order unity. This simple model predicts that the IHL fraction should have a small and nearly constant value below $M_{\text{host}} \approx 5 \times 10^{11} M_\odot$, $f_{\text{IHL}} \approx 5 \times 10^{-3}$. We expect a rapid rise in the IHL fraction with halo mass, $f_{\text{IHL}} \propto M^{3/2}$, for halos in the mass range $M_{\text{host}} \lesssim M_{\text{host}} \lesssim 20 M_\odot$. In physical units this range is $5 \times 10^{11} M_\odot \lesssim M_{\text{host}} \lesssim 10^{13} M_\odot$, and represents the range of transition between Milky-Way–like galaxies and small groups of galaxies. For host halos more massive than groups, $M_{\text{host}} \gtrsim 20 M_\odot$, both the relevant satellite halos and host halos fall along the power-law regime of the $M/L_\odot$ function and we expect the IHL fraction to remain roughly constant, $f_{\text{IHL}} \approx 40\%$.

At this point, it behooves us to summarize the points that this model illuminates regarding the IHL on different scales. In our model, it is approximately true that only the relative sizes of host and satellite objects determine the probability for satellites to deposit their stellar mass into the diffuse component. Halos acquire most of their mass, dark or stellar, in a relatively small number of accreting objects of order $1/20$ the size of the parent object (see Figs. 1 and 7 in the following section). Although the details are not known, it is an empirical fact that in a hierarchical cold dark matter cosmology, the process of galaxy formation must pick out a halo mass scale where galaxy formation is most efficient ($M_\ell \sim 5 \times 10^{11} M_\odot$), and that this efficiency drops at both lower and higher masses. Halos less massive than $\sim 20 M_\odot$ will accrete little stellar mass in satellite objects and thus have little opportunity to build a diffuse, stellar halo. Halos more massive than $\sim 20 M_\odot$ will accrete many satellite halos with masses such that they form stars near peak efficiency. As these host halos bring in satellites with lots of stars, they have ample opportunity to build diffuse stellar halos. The general conclusion that diffuse light fractions should increase from very small values in galaxy-sized systems to larger values in group– to cluster-sized systems seems difficult to avoid in the context of hierarchical cold dark matter structure formation.

4. RESULTS

4.1. IHL Fraction and Dark Halo Mass

The two panels of Figure 4 show our primary results. The predicted diffuse stellar mass fraction, $f_{\text{IHL}} \equiv M_{\text{diff}}/M_{\text{total}}$, is shown as a function of host halo mass. The total stellar mass $M_{\text{total}}$ includes the stellar mass in the diffuse component (IHL), satellite galaxies, and the central galaxy. In this section we will refer to the central galaxy as the “brightest halo galaxy” (BHG), in analogy with the brightest cluster galaxy (BCG) in clusters. The left panel shows results for case 1, in which we assign all light from disrupted subhalos to the diffuse component. The right panel shows case 2, in which we exclude any stars that were in subhalos having passed within $r_c$ of the host halo center from the diffuse component and instead add this material to the stellar mass of the central BHG. Diamonds show the average value of $f_{\text{IHL}}$, and the thin solid line shows the median. These results are derived from
1000 realizations for each host halo mass. The light and dark shaded regions span the 95% and 68% regions of the distribution, respectively, centered on the median.

The upper axis in the case 1 panel (left) of Figure 4 shows the luminosity of the central galaxy according to the Yang et al. (2003) mapping, while the case 2 panel (right) upper axis label gives the mean BHG luminosity at a given host mass that we obtained by averaging the total merged subhalo luminosity (plus the assigned central galaxy luminosity). We should note here that our case 2 model is not self-consistent, in that we first assign a central galaxy luminosity according to the $z = 0$ conditional luminosity function and then subsequently add stellar mass via subhalo mergers, which will obviously produce incorrect present-day stellar mass functions. However, on cluster scales, the case 2 central galaxy luminosities are many times larger than that required by the Yang et al. (2003) analysis (e.g., $L_{\text{BHG}} \propto 9 	imes 10^{11} L_\odot$ compared to $\sim 2 	imes 10^{11} L_\odot$ from Yang et al.), implying that even if our BHG were composed entirely of merged material (without any stellar mass produced by direct cooling processes), we would still overpredict the luminosity of the central object. We therefore present the case 2 analysis only as a means of minimizing intrahalo light production by dynamical considerations alone. We note that the result of this investigation, despite the above caveat, is only a systematically mild reduction in IHL across the full spectrum of host mass. Our rejection of case 2 aligns with the findings of Conroy et al. (2007) in which the authors use a numerically motivated model for the construction of massive galaxies and find that the large majority of centrally merging stellar mass ($\gtrsim 80\%$) must be ejected into the intracluster medium in order to reproduce the observed evolution of these central galaxies at low redshift.

The most obvious trend in Figure 4 is that the IHL fraction rises with halo mass from galaxy to group mass scales. On average the diffuse fraction is predicted to be negligible in $M \lesssim 10^{11} M_\odot$ halos and quite substantial in groups and clusters. This is independent of the method used to assign stripped stellar mass to the diffuse component or the central object. In both cases, the relation between $f_{\text{IHL}}$ and halo mass flattens considerably at masses above the group scale, tending toward a weaker evolution from a diffuse stellar mass fraction of about $f_{\text{IHL}} \sim 20\%$ at a host mass of $\sim 10^{14} M_\odot$, to a value of nearly $f_{\text{IHL}} \sim 30\%$ at $M_{\text{host}} \sim 10^{15} M_\odot$. We also see from the figure that the initial IHL fraction (without the inclusion of preprocessed diffuse stellar material) is virtually flat on cluster scales, implying that the a priori presence of subhalo IHL is largely responsible for the weak increase in the host’s total diffuse light on those scales. This mild trend has also been recovered by numerical simulations (Murante et al. 2004, 2007; Monaco et al. 2006), as well as observations of intracluster luminosity as a function of cluster richness (e.g., Zibetti et al. 2005).

In accordance with our simple model of the previous section, the trend of increasing IHL with halo mass is set primarily by the convolution of the distribution of subhalos that are disrupted (Fig. 1) with the mass-to-light ratios of halos (Fig. 2). Consequently, the trends predicted by our full model follow closely our general expectations described in §3. Specifically, galaxy halos with $M \approx M_\odot \approx 5 \times 10^{11} M_\odot$ have massive central galaxies because they sit in the valley of the $M/L_c$ curve; however, these galaxies have low diffuse light contributions because they accrete and destroy most of their mass in subhalos of mass $M \approx 2.5 \times 10^{10} M_\odot$, where star formation is inefficient. Halos at the group scale ($\sim 10^{13} M_\odot$) accrete large numbers of subhalos near the valley of the mass-to-light ratio curve. These accreted satellites are a copious source of stellar material for diffuse light in groups. The diffuse light fraction begins to flatten above the group scale because both the host and destroyed subhalos have masses $M \gtrsim M_\odot$, which corresponds to a regime where the $M/L_c$ relation follows an approximate power law. In this case, the ratio of destroyed satellite luminosity to central host luminosity is independent of mass, $L_c(M_{\text{sat}})/L_c(M_{\text{host}}) \approx \text{constant}$. We note here that there is also a subdominant effect that contributes to the flattening of $f_{\text{IHL}}$ at high masses, namely, that more massive host systems typically accrete their material more recently. This leaves relatively little time to disrupt satellites (see Z05) and results in a lower fraction of diffuse, stripped material.

In order to explore how the total stellar mass within halos is divided among the various components (IHL, BHGs, satellites) and to more directly compare our results with the variety of observational estimates in the literature, Figures 5 and 6 show two alternative quantities. In Figure 5, we ignore surviving satellite galaxies altogether in order to determine the relative importance of IHL as compared to the total stellar mass in the BHG + IHL. In case 1 (left) the IHL dominates the BHG on cluster scales, contributing 80%–90% of the combined stellar mass, while the
fraction $\text{IHL}/(\text{IHL} + \text{BHG})$ declines to $\sim 1\%$ on galaxies scales, where it is nearly identical to our definition of the intrahalo light fraction. Again, this is easy to understand in terms of the empirically determined mass-to-light ratios of halos in hierarchical dark matter cosmologies. On galaxy scales, the host halo forms stars at near maximal efficiency, while its accreted substructures carry comparatively little stellar mass. The $\text{IHL}/(\text{IHL} + \text{BHG})$ fraction is nearly equal to $f_{\text{IHL}}$ because nearly all of the luminosity in nondiffuse (or, for that matter, diffuse) form is in the BHG. As host halo mass increases, the efficiency of galaxy formation in the central system itself declines, meaning relatively more of the nondiffuse light is carried by the satellites that are not shedded. This causes the $\text{IHL}/(\text{IHL} + \text{BHG})$ fraction to increase more rapidly with mass than $f_{\text{IHL}}$. Importantly, our result compares favorably to the $\sim 80\%$ IHL to IHL + BHG fraction found by Gonzalez et al. (2005) in galaxy clusters.

Figure 6 depicts a related quantity, the IHL + BHG fraction relative to the total stellar mass. The IHL + BHG fraction is anti-correlated with host mass, decreasing from $\sim 40\%$ on group scales to $\sim 30\%$ within large clusters. The trend follows from the same logic used in the previous paragraph. In addition to the evolution of $f_{\text{IHL}}$ with mass, the BHG becomes increasingly less luminous relative to the sum of the luminosities of its satellite galaxies as halo mass increases. The open points with error bars show the same quantity derived observationally for individual clusters and groups by Gonzalez et al. (2007). The predicted and observed trends are remarkably consistent, especially on average. Given the observational uncertainties, the variance in the observed points at fixed mass is also consistent with our prediction; however, there is a tendency for the data points to skew into the upper range of our model’s scatter. This may reflect a bias in the observational sample, which is selected to include systems with dominant BHGs. Indeed, a positive trend between dominance of the central BHG and IHL fraction is seen in our models (see § 4.2).

Figure 7 shows the average fraction of diffuse light that comes from satellite galaxies of a given stellar mass $M_*$, for several choices of host dark matter halo mass. We see that the diffuse component (or stellar halo) around small $M_{\text{host}} \sim 10^{11} M_\odot$ (e.g., M33) dark matter halos is built up from disrupted dwarf spheroidal-type galaxies with $M_* \sim 10^6 M_\odot$. Stellar halos around larger Milky-Way-type galaxies, $M_{\text{host}} \sim 10^{12} M_\odot$, are built from dwarf-irregular-size systems, $M_* \sim 10^{8.5} M_\odot$, and intracluster light is produced by massive galaxies, $M_* \sim 10^{11} M_\odot$ (see Murante et al. 2007 for a similar result from numerical simulations of intracluster stars). This fact is likely to be an important ingredient in understanding the metallicities of diffuse stellar components as a function of galaxy luminosity (Mouhcine et al. 2005; Ferguson 2007); specifically, more luminous galaxies are expected to be surrounded by more metal-rich stellar halos because their halos are formed from more massive satellites. In addition, note that the differential stellar mass distributions become more sharply peaked as host halo mass increases from galaxies to groups, reflecting the increase in relative subhalo luminosity as we approach the $M \sim M_*$ valley in the $M/L_*$ relation (Fig. 2). Correspondingly, the distributions broaden once more as we consider the most massive hosts because their subhalo populations have moved in large part to the right of the valley.

4.2. The Distribution of the Diffuse Light Fraction at Fixed Halo Mass

A second important feature of the diffuse stellar mass fraction is the relative scatter at fixed mass, particularly in low-mass halos. The width of the distribution is driven primarily by differences in mass accretion histories of objects of fixed final halo mass, including the stochastically driven properties of the host’s recent merger events and the particular orbital parameters for each plunging satellite. As a general rule, we expect halos that acquired their mass more recently to have had relatively less time to disrupt the subhalos they host and to have less IHL, while early-forming host halos will display the opposite behavior. Continuing with this logic, the number of bound satellite galaxies should anticorrelate with the IHL fraction in objects. Indeed, Figure 8 illustrates that our model predicts just such an anticorrelation between satellite galaxy abundance and IHL fraction. Of particular note is the tight correlation that emerges for groups-scale objects when considering only the brightest of the survivors within the groups. Our analysis indicates that for galaxy-sized halos, the $68\%$ scatter in each $N_{\text{surv}}$ bin differs by roughly a factor of 2 from the bin’s median value and is approximately constant across the range of $N_{\text{surv}}$. In group-scale hosts, the variance is generally smaller ($\sim 0.1$–$0.2$ in $\log_{10}(N_{\text{surv}})$) and increases slowly as the number of surviving massive galaxies grows.

This result may explain why some of the Gonzalez et al. (2007) clusters have higher IHL fractions than we predict (e.g., Fig. 6). These clusters were selected to have clearly dominant BHGs—in other words, to have a less dominant bright satellite population. Based on Figure 8, we would expect these systems to have higher IHL fractions than typical clusters of the same mass.

4.3. Tests for Robustness

To be sure, our model has several uncertain and poorly constrained elements. Particular examples include the criterion for
Fig. 7.— Similar to Fig. 1, the differential contribution to the stellar mass from subhalos with an initial stellar mass \( M_\ast \), as a function of \( M_\ast \). We show this differential contribution for five host halo masses indicated in the legends of the figure. Dashed lines indicate stellar material contributed by disrupted satellite galaxies, while dot-dashed lines indicate the fraction of stellar mass in surviving subhalos for a particular host. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 8.— Median diffuse light fraction (case 1) at fixed host mass as a function of the number of massive satellites surviving over the halo’s history. In the left panel we focus on \( 10^{12} M_\odot \) halos (median \( f_{\text{IHL}} \sim 1.7\%\)) and look at the number of surviving subhalos with more stellar mass than \( M_\ast = 10^9 \) (diamonds) and \( M_\ast = 10^8 M_\odot \) (squares). In the right panel we consider a more massive, \( 10^{13.5} M_\odot \) host halo and show the diffuse light fraction (median \( f_{\text{IHL}} \sim 16\%\)) as a function of surviving subhalos with more stellar mass than \( M_\ast = 10^{10} M_\odot \) (diamonds) and \( M_\ast = 10^{9.5} M_\odot \) (squares). Although not shown here, the 68% scatter about the median for the \( 10^{12} M_\odot \) host is roughly constant at \( \sim \pm 0.3 \) in \( \log_{10} \), while the \( 10^{13.5} M_\odot \) host exhibits a smaller variance of \( \sim \pm 0.1 \)–\( 0.2 \) in \( \log_{10} \) that grows slightly as \( N_{\text{surv}} \) increases. [See the electronic edition of the Journal for a color version of this figure.]
removing light from bound satellites and assigning it to the IHL, as well as the evolution of stellar mass with time. Our argument in § 3 indicates that the overall trends for the IHL that we describe are set primarily by the convolution of the mass function of accreted subhalos with the mass-to-light ratios of accreted objects as a function of mass. Further, because we are interested in the IHL fraction relative to the total luminosity of the system, errors in the normalization of the stellar mass function tend to offset each other, if not divide out precisely. These lines of reasoning suggest that the IHL trends that we outline should be robust, at least at the qualitative level, but likely at the quantitative level as well. Nevertheless, we have subjected our model to significant variations in parameter values to assess the robustness of the fiducial result.

Our free parameters govern

1. dark halo and galaxy disruption via $f_{\text{cen}}$—the fraction of the initial halo circular velocity that defines the critical circular velocity below which satellite galaxies are deemed “disrupted” and their stellar mass is added to the diffuse light;
2. star formation via $\alpha$—the star formation parameter defined in eq. (2);
3. and galaxy luminosities via $M/L_c$ as a function of mass—the function set from large-scale galactic observations to relate central galaxy luminosities and dark halo masses.

In Figure 9 we plot the median IHL fraction computed for our fiducial model parameters (thick solid line) along with various other choices. Note that for simplicity we have neglected the “preprocessed” IHL contribution in this set of tests. We find that changing the star formation parameter $\alpha$ over a very wide range (0.5 $< \alpha < 2$) produces global IHL trends that differ by less than a factor of 2 from the fiducial case. Predictably, the choice of $f_{\text{cen}} = 0.15$ with fiducial star formation ($\alpha = 1$) results in less diffuse light across the full mass range because a dark matter subhalo is required to be more severely affected by the host potential before relinquishing its mass to the IHL. However, even this drastic adjustment to $f_{\text{cen}}$ produces IHL values that are within a factor of 2 of the fiducial result.

The most visible change to our main result comes from revising our adopted $M/L$, from the Yang et al. (2003) inference to an alternative form advocated by Vale & Ostriker (2004) (see Fig. 2). The Vale & Ostriker (2004) $M/L_c$ relation has a steeper “valley” and, as could be expected from our discussion in § 3, gives rise to a steeper $f_{\text{IHL}}$ relation. Even in this case, the overall increase in IHL is no greater than a factor of $\sim 2$ at the cluster scale, while the steep faint-end slope of the Vale & Ostriker $M/L_c$ relation suppresses the diffuse light in small galaxies to below fiducial levels. Despite our limited knowledge of star formation, the overall trend appears robust. The sensitivity of the IHL fraction to the assumed mass-to-light ratios for infalling objects over the range within which the mass-to-light ratios can be reliably constrained suggests that the uncertainty in this ingredient is a fundamental limitation to the quantitative accuracy of any study based on this or similar approaches. In particular, the IHL in group-sized systems relies on the precise location of the $M \sim M_c$ trough in Figure 2. Alternatively, Figure 9 indicates that it may be possible in the future to constrain the $M/L_c$ relation between small halos and central galaxies by measuring the slope of the IHL fraction as a function of host halo mass, although more accurate theoretical methods would need to be employed in order to bring this goal to fruition.

We have managed, throughout this paper thus far, to avoid concerning ourselves too much with the baryon dynamics that play a significant role in the central regions of the halos that comprise our dark matter model. However, in the innermost kpc of a dark matter halo, the mass density can be dominated by baryonic material, thereby increasing the concentration parameter typically assigned to an NFW density profile and making subhalos harder to disrupt. The response of the dark matter profile to the presence of these cooling baryons is often modeled via adiabatic contraction (AC) (see, e.g., Blumenthal et al. 1986; Gnedin et al. 2004). In cosmological simulations incorporating radiative cooling as well as star formation and supernova feedback, Rudd et al. (2007) find that the effects of baryon contraction can be approximated by increasing halo concentrations at fixed mass by a uniform factor, nearly constant over the mass regime of relevance and slightly smaller than a factor of 2. Since this adjustment applies to host halos as well as subhalos, the effect is two-fold: satellites become relatively more resistant to disruption, while their hosts have higher central densities and stronger tidal fields as a result of this contraction. In order to test the robustness of our model to these competing phenomena, we double the initial concentration parameters of each host halo and subhalo. The resultant IHL fraction, shown in Figure 9, has a slightly shallower slope in the “break” between power-law $M/L$ regimes, although the galactic-scale diffuse light is slightly larger that of the fiducial case 1, and the intracluster stellar mass decreases by less than a factor of 2. Overall, the effect is less important than some of the other uncertainties we consider here. We interpret the relative changes from our fiducial model to be a consequence of the fact that the IHL in larger host halos is governed by the disruption of subhalos that are relatively small in comparison to the host, $\sim 10^{11.5} M_\odot$. These satellites will be more resistant to tidal disruption if they are contracted. The IHL in small hosts is set by the most massive
subhalos that merge, and these systems are strongly affected by dynamical friction. The dynamical friction force in the host halo will be enhanced because of the contraction and this enhances massive satellite destruction probability.

In closing, we reiterate that IHL fractions will be naturally less susceptible to fiducial normalizations, and that our intrahalo light predictions are driven primarily by the shape of the $M/L_c$ function convolved with the accretion histories of Figure 1. We conclude that our general prediction is robust; explicitly stated, that the IHL fraction should rise from a very small value $\leq 1\%$ in low-mass galaxies to an appreciable fraction $\geq 20\%$ in cluster-sized systems.

5. DISCUSSION

The main conclusions of our work may be summarized as follows:

1. The IHL fraction in dark matter halos of mass $M$ is expected to increase dramatically from $\sim 0.5\%$ to $\sim 20\%$ as we examine systems from the size of small spiral galaxies ($M \sim 10^{11} M_\odot$) to galaxy groups ($M \sim 10^{13} M_\odot$). The IHL-mass relation becomes flatter at a value of $\sim 20\%$ for $M \gtrsim 10^{13} M_\odot$, increasing weakly thereafter to $\sim 30\%$ for host halos of mass $M \sim 10^{15} M_\odot$. While varying the empirical mapping between halo mass and galaxy luminosity can produce a slightly higher cluster IHL fraction, $\sim 40\%$, the overall trends are very robust and are governed by the well-known fact that galaxy formation efficiency varies as a function of mass scale while dark matter accretion processes are roughly self-similar. Specifically, the subhalos that “build” galaxy halos have much lower luminous mass fractions than the subhalos that build galaxy groups.

2. The IHL component within galaxy halos is dominated by the disruption of satellites of stellar mass $\sim 10^{8.5} M_\odot$, while the IHL component in clusters is built from more massive stellar systems $\sim 10^{11} M_\odot$. We expect that more massive galaxies will therefore be surrounded by more metal rich stellar halos, as has been suggested by recent observations (Mouhcine et al. 2005), although Ferguson [2007] disputes this claim.

3. The variation in IHL fraction from system to system at a fixed halo mass is driven by variations in the accretion history. Systems with fewer surviving satellites tend to have higher diffuse light fractions. The scatter at fixed mass is larger in galaxy-sized halos because the light tends to be dominated by a small number of massive satellite accretion events. As indicated by Figure 8, the number of surviving satellite galaxies in a group is expected to negatively correlate with that group’s IHL fraction, providing an observational expectation that future surveys may potentially address. This phenomenon may also provide insight regarding the comparison of our results to observation, in which Gonzalez et al. (2007) find a slightly higher IHL fraction than our model predicts for group-scale hosts, possibly due to a selection effect in which their sample systems are typically dominated by their central galaxies, with relatively few bright satellites and thus a systematically larger IHL value.

Current observations place loose constraints on the diffuse light fraction on every mass scale. By all indications, IHL accounts for less than a few percent of the total stellar mass in large galaxy-sized host halos (see Siegel et al. 2002; Guhathakurta et al. 2005 for discussions concerning the Galactic halo and that of M31, respectively), while the diffuse stellar components of cluster-sized hosts are typically about 1 order of magnitude higher (Mihos et al. 2005; Zibetti et al. 2005; Krick et al. 2006; Gonzalez et al. 2007). A pronounced “break” in the diffuse light below the cluster scale is even reported (Ciardullo et al. 2004). These results are in general agreement with our expectations.

We predict that the diffuse component around small spiral galaxies will contain a very small fraction of the primary galaxy’s light on average, $f_{\text{IHL}} \leq 1\%$. It is interesting to consider the surface brightness limit that may be required to observe such a diffuse component. In Figure 10 we investigate a simple example case where we have distributed all of the diffuse light predicted for a low-luminosity galaxy, $L_c \sim 4 \times 10^9 L_\odot$, into an NFW halo density profile that mirrors that of the host halo. Solid and dashed lines correspond to the median and 95 percentile predictions. Here, we have assumed a stellar mass-to-light ratio of 1 in the $R$ band. For reference we also plot the exponential surface brightness profile (Kim et al. 2004) for the disk of a system of comparable luminosity, the Sculptor group galaxy NGC 300, which was shown by Bland-Hawthorn et al. (2005) to extend $\sim 15$ kpc from the galaxy’s center without revealing any underlying diffuse component. According to our analysis, a survey reaching $\sim 17$ kpc from the galaxy’s center and achieving 32 mag per arcsec$^{-2}$ might be able to detect a stellar halo around NGC 300 if the diffuse component is comparatively bright, while a more average IHL value for the system would require an even deeper search. Similar analyses for Milky-Way-sized stellar halos indicate that the IHL begins to separate itself from a (face-on) disk profile at roughly 29–32 mag per arcsec$^{-2}$, which is in line with the results of Irwin et al. (2005) for M31. This provides some idea of the observational depth that will, in the future, be required to identify remote stellar halos around small spiral galaxies. It is worth pointing out that some fraction of this light may be in the form of recently destroyed satellites, which should produce higher surface brightness features and will be more easily seen (e.g., Bullock & Johnston 2005). Of course, the likelihood of a recent accretion will decrease for lower mass galaxies. A more detailed investigation of these issues is warranted, but the complexity inherent in studying these issues places such an attempt beyond the scope of this paper.

It is worth noting that while we have focused on accreted material as the source of diffuse light, several other sources have been discussed. These include in situ star formation (Gerhard et al.
2002), ejection from binary systems (Holley-Bockelmann et al. 2005), dry mergers (in clusters) between ellipticals (Stanghellini et al. 2006), and collisionless evaporation (Mucciarelli & Ciotti 2004). However, as this work demonstrates, galaxy disruption provides a reasonable and seemingly inevitable mechanism for producing IHL on all scales, although these phenomena almost certainly have some subdominant role in the build up of a host halo’s diffuse light.

According to our picture, the driving force behind the creation of IHL on every mass scale is the stellar mass spectrum of intrahalo progenitors (Fig. 7). The properties of a system’s diffuse luminous component can be understood as the result of the stochastically driven merger history of stellar-rich satellite galaxies, indicating that future observations of intrahalo light could be used as a probe of a galaxy’s merger history. The predicted trend with IHL fraction and halo mass is certainly within the scope of future observational work. Interestingly, preliminary results from the Galaxy Halos, Outer disks, Substructure, Thick Disks, and Star Clusters (GHOSTS) survey (de Jong et al. 2007) suggest that the stellar halos of low-mass galaxies are, indeed, less prominent than those of more massive galaxies. Ongoing surveys of this type will be able to test whether the expected trend carries over to other mass regimes. As we demonstrated in Figure 9, while the qualitative trend between IHL fraction and halo mass is robust, the slope of the relation is sensitive to the underlying relationship between halo virial mass and galaxy luminosity on dwarf galaxy scales. In principle, this measurement, in concert with models of the kind we present, will help constrain the nature of galaxy formation in dwarf-irregular-sized halos and test the accretion histories of dark halos on small scales.

We would like to thank JoelBerrier, Scott Chapman, Roelof de Jong, Annette Ferguson, Fabio Gastaldello, Kathryn Johnston, Jason Kalirai, Tammy Smecker-Hane, Risa Wechsler, and Xiaohu Yang for useful discussions. Advice from Joss Bland-Hawthorn, John Feldmeier, Anthony Gonzalez, Andrey Kravtsov, and Dennis Zaritsky greatly improved the paper and led to the creation of Figures 5, 6, and 10. We also thank the anonymous referee for suggestions that improved the quality of the paper. C. W. P. and J. S. B. are supported by National Science Foundation (NSF) grants AST 06-07377 and AST 05-07816, and the Center for Cosmology at UC Irvine. A. R. Z. is funded by the Kavli Institute for Cosmological Physics at the University of Chicago, by the NSF under grant PHY-0114422, and by the National Science Foundation Astronomy and Astrophysics Postdoctoral Fellowship program under grant AST 06-02122.

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