

Constraints on intragroup stellar mass from hostless Type Ia supernovae

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ABSTRACT

We probe the diffuse stellar mass in a sample of 1401 low-redshift galaxy groups (10^{13} – $10^{14} h^{-1} M_{\odot}$) by examining the rate of hostless Type Ia supernovae (SNe Ia) within the groups. We correlate the sample of confirmed SNe Ia from the Sloan Digital Sky Survey SN survey with the positions of our galaxy groups, as well as with the resolved galaxies within them. We find that 19 of the 59 SNe Ia within the group sample have no detectable host galaxy, with another three ambiguous instances. This gives a robust upper limit that a maximum of $2.69_{-1.34}^{+1.58}$ per cent of the group’s total mass arises from diffuse stars in the intragroup medium. After correcting for a contribution from ‘prompt’ SNe occurring within galaxies, and including a contribution from those which arise in dwarf galaxies below our photometric limit, we find that only $1.32_{-0.70}^{+0.78}$ per cent of the group’s total mass is likely in the form of diffuse stellar mass. Combining this result with the galaxy stellar mass functions of Yang, Mo and van den Bosch, we find that 47_{-15}^{+16} per cent of the *stellar mass* in our groups is in the form of diffuse light, so that stars make up a fraction $0.028_{-0.010}^{+0.011}$ of the *total* group mass. Galaxy groups appear to be very efficient in disrupting stellar mass into a diffuse component; however, stars still make up a small fraction of the group mass, comparable to that seen in rich clusters. This remains a challenge to galaxy formation models.

Key words: galaxies: evolution – galaxies: formation – galaxies: structure.

1 INTRODUCTION

Diffuse light in the haloes of galaxy clusters has been extensively studied since the discovery of ‘swarms of stars’ between galaxies in the Coma cluster by Zwicky (1951). Although puzzling at the time, diffuse stellar light is now thought to be a natural consequence of hierarchical structure formation, which causes merging galaxies to shed some of their stellar material (Willman et al. 2004; Purcell, Bullock & Zentner 2007). The diffuse light in individual massive clusters has been the focus of many observational studies, which find that the fraction of the total cluster light in this component is 10–30 per cent (e.g. Thuan & Kormendy 1977; Scheick & Kuhn 1994). By stacking ~ 700 clusters, Zibetti et al. (2005) was able to tightly constrain the diffuse light within 500 kpc of the cluster centre to be 10.9 ± 5.0 per cent of the total cluster light.

At the other extreme, the diffuse light around galaxies like the Milky Way is similarly thought to arise from the tidal heating and stripping of infalling dwarf galaxies (e.g. Searle & Zinn 1978; Bullock, Kravtsov & Weinberg 2001; Font et al. 2008). However, in this regime, the fraction is only ~ 1 –2 per cent of the total light in the halo (e.g. Chiba & Beers 2000; Yanny et al. 2000; Law, Johnston & Majewski 2005). Probing the intermediate halo mass regime, that of

galaxy groups, is important in order to reconcile these two extreme regimes.

Galaxy groups are difficult to observe observationally and thus a study of the intragroup medium (IGM) in typical systems has not been done. Studies of the more extreme compact groups have found a large variation in the group-to-group diffuse light, ranging from 5 per cent up to as much as 45 per cent of the total light (White et al. 2003; Da Rocha & Mendes de Oliveira 2005; Da Rocha, Ziegler & Mendes de Oliveira 2008).

Galaxy groups have velocity dispersions comparable to that of the most massive galaxies within them, and as such are a prime location for the mergers, tidal stripping and shredding which is thought to give rise to the diffuse light. Thus, the amount of diffuse stellar mass in galaxy groups is a direct probe of the efficiency with which infalling galaxies are disrupted. This could have important implications for semi-analytic models, which produce too many faint red galaxies (Weinmann et al. 2006; Gilbank & Balogh 2008).

Type Ia supernovae (SNe Ia) likely result when a carbon–oxygen white dwarf acquires additional mass from a companion star, which causes a thermonuclear explosion. However, the exact origin of the progenitor material is uncertain, which makes direct prediction of SN Ia rates from stellar population modelling difficult. It is typical to parametrize the rate and then measure the coefficients empirically. The most common model for the SN Ia rate is the so-called A+B model, which assumes that SNe Ia arise from two distinct channels.

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In this model, there is a ‘prompt’ component which depends on the current star formation rate (SFR) of the host and a ‘delayed’ component which traces the host’s stellar mass (Scannapieco & Bildsten 2005; Graham et al. 2008). This model was motivated by the observation that the SN Ia rate is ~ 20 – 30 times higher in late-type galaxies than in early-type galaxies of the same mass (Mannucci et al. 2005).

Relatively little attention has been given to SNe which may be hosted by diffuse material within groups and clusters. But Gal-Yam et al. (2003) found that two of the seven cluster SNe Ia discovered during a survey of low-redshift Abell clusters were not associated with galaxies. Recently, Sand et al. (2008) have begun a search of 60 X-ray-selected galaxy clusters with the expectation of finding ~ 10 intracluster SNe Ia. They identified three intracluster candidates in early data, all of which were actually outside of R_{200} , implying a relative deficit of intracluster mass at small cluster radii.

This Letter is complementary to these studies, as we constrain the diffuse stellar mass in relatively low-mass galaxy groups, by correlating SNe Ia with a large group catalogue, to identify SNe without a resolved galaxy host. In Section 2, we discuss our SN and group sample, as well as introducing the derived galaxy properties we use. In Section 3, we discuss the procedure we use to identify the hosts or lack of hosts of the SNe. Finally, in Section 4, we discuss the constraints this places on the diffuse stellar mass in galaxy groups. Throughout this Letter, we adopt, as was done during the assembly of the group catalogue, a Λ cold dark matter (Λ CDM) cosmology with the parameters of the third year *Wilkinson Microwave Anisotropy Probe* data, namely $\Omega_m = 0.238$, $\Omega_\Lambda = 0.762$, $\Omega_b = 0.042$, $n = 0.951$, $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) = 0.73$ and $\sigma_8 = 0.75$ (Spergel et al. 2007).

2 DATA

In this Letter, we require a uniformly selected sample of SNe Ia and a large sample of galaxy groups over a large area of the sky to find enough hostless SNe Ia to constrain the diffuse stellar mass. Therefore, we will examine the region of Stripe 82 in the Sloan Digital Sky Survey (SDSS) which hosts the SDSS SN survey.

2.1 SDSS supernova survey

The SDSS SN survey was designed to identify SNe Ia at low redshift ($0.05 < z < 0.35$) by imaging an area of 300 deg^2 multiple times over a period of 5 yr (Frieman et al. 2008). Once identified, the SNe Ia candidates are spectroscopically followed up and classified (Sako et al. 2008; Zheng et al. 2008). This has resulted in the largest collection of SN at low redshift. Crucially, for our purposes, the scanning throughout the 300 deg^2 is very uniform, resulting in a consistent detection threshold. For the following, we restrict our analysis to the 368 confirmed SNe Ia within $0.1 < z < 0.2$. We note that the SDSS SN survey also identifies Type II SNe. However, despite being more numerous, they are also much fainter (Bazin et al. 2009). Thus, spectroscopic follow-up of Type II SNe was limited to those at $z < 0.06$, which is below our redshift limit.

2.2 Group catalogue

Reliable and representative samples of galaxy groups can be found using friends-of-friends algorithms in large redshift surveys (e.g. Huchra & Geller 1982; Carlberg et al. 2001; Berlind et al. 2006). We use a highly complete group sample defined by Yang

et al. (2007), who have applied their ‘friends-of-friends’-like algorithm to the SDSS fourth data release to produce a sample of $\sim 300\,000$ galaxy groups with masses as low as $10^{11.5} h^{-1} M_\odot$. An important aspect in the construction of this group catalogue is the subsequent mass estimates, which are obtained by essentially ranking groups by their total luminosity or total stellar mass and associating these rankings with the expectations of a Λ CDM halo occupation model. We use ‘Sample I’ from Yang et al. (2007), which exclusively uses galaxies with SDSS spectroscopic redshifts. We chose this sample, as opposed to the other samples, which add in existing redshifts from the literature, because we are principally concerned with obtaining a uniformly selected population of galaxy groups. In this Letter, we use the halo mass rankings obtained from the total group stellar mass and restrict our analysis to groups with masses greater than $10^{13} h^{-1} M_\odot$, which leaves a final sample of 1401 groups between $z = 0.1$ and 0.2 within the SDSS SN legacy survey area. The galaxy groups have a median halo mass of $1.98 \times 10^{13} h^{-1} M_\odot$ and a mean value of $3.86 \times 10^{13} h^{-1} M_\odot$ with a standard deviation of $3.16 \times 10^{13} h^{-1} M_\odot$.

We make use of measurements of the stellar mass and SFRs of the galaxies within the main galaxy spectroscopic sample of the SDSS. Our stellar masses are taken from Kauffmann et al. (2003), and were determined by comparing large libraries of stellar population models with line indices and broad-band photometry. The SFRs we use were measured by Brinchmann et al. (2004) using principally H α emission along with continuum properties (e.g. 4000-Å break).

3 HOSTED AND HOSTLESS GROUP SNe Ia

Our goal is to obtain a complete sample of SNe Ia which reside within galaxy groups in our sample. We define group membership as those SNe Ia which are within the projected group virial radius and which are $\pm 3000 \text{ km s}^{-1}$ from the group redshift. This velocity range is larger than the typical velocity dispersion of our groups, but is chosen to be 2σ of the precision with which redshifts can be derived from SNe Ia spectral features (i.e. $\sim 1500 \text{ km s}^{-1}$; Frieman et al. 2008; Cooper, Newman & Yan 2009). Of the 368 SNe Ia in our complete sample, 59 are matched to one of our galaxy groups.

We search for host galaxies of the 59 group SNe, by matching to all group galaxies in the main galaxy sample of SDSS. We assume an SN is hosted if it is within a distance equal to twice the size of the radius enclosing 90 per cent of the galaxy’s light. This radius corresponds to a physical scale of 9 – $14 \text{ kpc } h^{-1}$ for most of the galaxies in the spectroscopic sample, and is slightly smaller for those in the photometric sample. However, for a few of the bright group/cluster galaxies this distance is much larger because of their extended haloes. For this reason, we have capped the search radius to be a maximum of $40 \text{ kpc } h^{-1}$. In practice, this changes the membership of just one SNe, which is $78 \text{ kpc } h^{-1}$ from a BCG. By matching within our search radius and a velocity window of $\pm 3000 \text{ km s}^{-1}$, we find that 23 of the 59 group SNe are hosted by galaxies within the main spectroscopic galaxy sample. The spectroscopic galaxy sample only reaches a magnitude limit of $r = 17.77$, so we must extend our search for the hosts of the remaining SNe to the photometric catalogues, which reach 95 per cent completeness at $r \sim 22.2$. This is an absolute magnitude of $M_r \approx -15$ to -16 in our sample. We search for hosts of the remaining SNe in the photometric catalogues again within our scaled radius, and now use the photometric redshifts supplied by the SDSS pipeline. 14 of the remaining 36 SNe were matched with host galaxies using this criteria. Finally, we relax the requirement that the galaxy photometric redshift is within the range of the SN spectroscopic redshift and find

that an additional three galaxies are matched. This leaves us with a sample of 19 SNe with no host galaxy in the photometric catalogue. The images of these SNe, as with the entire sample, were visually inspected to confirm that they appeared as truly hostless SNe. Given the limit of our photometric catalogue, we might expect that some of these 19 SNe are actually hosted by galaxies which are below our detection threshold. Integrating the r -band luminosity function of SDSS at $z \sim 0.1$ (Blanton et al. 2003), only 3 per cent of the total galaxy luminosity is below our detection limit. If we adopt a luminosity function typical of rich galaxy clusters, which have a steep faint end slope (Milne et al. 2007), as much as 5 per cent of the total galaxy luminosity may go undetected in our images. Thus, if the number of SN scale with luminosity, then it is likely that $\sim 2 \pm 1$ of the apparently hostless galaxies are actually hosted by very faint galaxies (all uncertainties are 1σ). In summary, we find that of the 59 total group SNe, 23 are matched to spectroscopically confirmed galaxy, 14 are matched to galaxy via photometric redshift and a further three appear associated with other galaxies. This leaves a sample of 19 apparently hostless SNe.

4 RESULTS

We are first interested in the distribution of the SNe Ia sample within our galaxy groups. This is presented in Fig. 1, in which we show the SN Ia per area per group as a function of groupcentric distance in units of R_{180} as calculated in Yang et al. (2007). The SN Ia counts per area decline steeply with groupcentric distance, which indicate that they are associated with the galaxy group. Also shown is the rate of SN Ia hosted by group galaxies within the spectroscopic sample. Given the small numbers and uncertainty on each point, the distributions are similar. There is no evidence that the hostless SN, and thus the diffuse stellar mass, are distributed differently from the galaxy population.

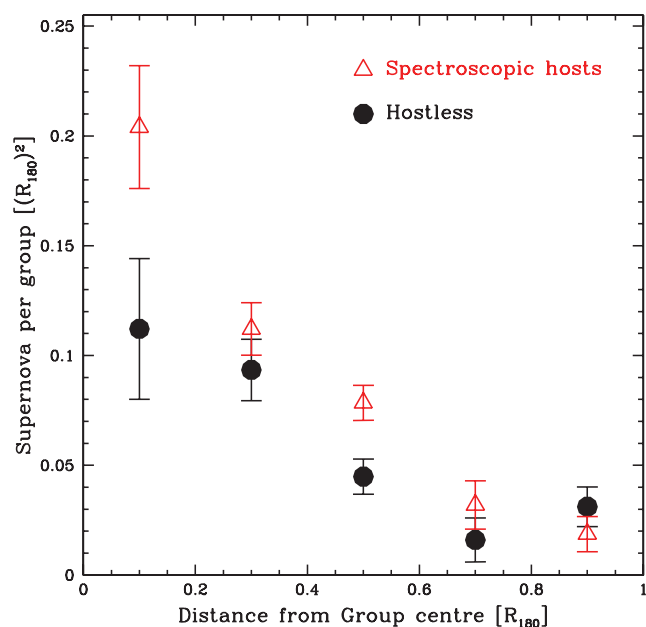


Figure 1. The distribution of SNe Ia as a function of distance from the group centre. The red triangles represent the rate of SNe Ia hosted by the sample of spectroscopic galaxies with the group, while black circles signify the rate of hostless SNe Ia within the group sample. R_{180} corresponds to a distance of $0.79 h^{-1}$ Mpc for a group with the mean mass of our sample ($3.86 \times 10^{13} h^{-1} M_{\odot}$).

Assuming that all 19 apparently hostless galaxies are truly hostless, and making the simplifying assumption that the stellar population in the IGM is the same as within the group galaxies, our measurement immediately tells us the diffuse stellar mass represents $\sim 32^{+4}_{-3}$ per cent of the total stellar mass in these groups, where the quoted statistical uncertainty is the 1σ confidence limit. We now explore the systematic uncertainties and consequences associated with this measurement.

4.1 Upper limit on the diffuse group stellar mass

As discussed above, without a definite model of the origin of SNe Ia, the conversion of a SNe number count into the underlying stellar mass is uncertain. Therefore, we first try to derive the *maximum* diffuse stellar mass possible given the population of hostless SNe Ia. First, we will assume that the 22 SN without a spectroscopic or photo- z confirmed host are true descendants of diffuse group stellar mass. This includes the 19 SN with no apparent host as well as three which appear to be located within galaxies, but whose galaxies have photometric redshifts inconsistent with both the SN redshift and the redshift of the group. To obtain a robust upper limit, we here further assume that there is no contribution from faint, undetected hosts. It is worth pointing out that this is also an upper limit because it is much easier to detect SNe Ia in hostless environments, where the contrast is high, than it is for those which occur in galaxies. We will assume that the remaining 37 SN occur within galaxies.

We now need to derive a relation between the stellar mass and the number of resulting ‘delayed’ SN. To do this, we must accurately know the stellar mass and SFR of a population of galaxies. We will use our sample of galaxies which are spectroscopically confirmed and which are within our groups. Using the stellar masses of Kauffmann et al. (2003), we find that the spectroscopic sample of galaxies in our 1401 groups has a total stellar mass of $6.55 \times 10^{14} h^{-1} M_{\odot}$ and, using the SFRs of Brinchmann et al. (2004), the total SFR is $2.62 \times 10^4 h^{-1} M_{\odot} \text{ yr}^{-1}$. We can now use the empirical relation of Dilday et al. (2008), which was derived from the SDSS SN survey, to find out how many of the 23 SNe in the spectroscopic sample are ‘prompt’ SN and how many are ‘delayed’. Dilday et al. find that the SN rate, r , is given by $r = A\rho + B\dot{\rho}$, where ρ is the stellar mass, $\dot{\rho}$ is the SFR, $A = 2.8 \pm 1.2 \times 10^{-14} \text{ SNe } M_{\odot}^{-1} \text{ yr}^{-1}$ and $B = 9.3^{+3.4}_{-3.1} \times 10^{-4} \text{ SNe } M_{\odot}^{-1}$. Using this formula, we find that 43^{+18}_{-16} per cent of 23 SNe are ‘delayed’ and 57^{+16}_{-18} per cent are ‘prompt’. So, we see that there are $9.9^{+4.1}_{-3.9}$ ‘delayed’ SNe ($=43^{+18}_{-16}$ per cent $\times 23$), which arise from an underlying stellar mass of $6.55 \times 10^{14} h^{-1} M_{\odot}$. Thus, we have the relation that one delayed SN arises from an underlying stellar mass of $6.62^{+3.92}_{-3.54} \times 10^{13} h^{-1} M_{\odot}$. We will use this relation throughout the rest of the Letter to relate the stellar mass to a quantity of delayed SNe.

The diffuse stellar mass is expected to be relatively old, as the intragroup mass is not expected to be able to form stars *in situ*. Any star formation which results from the stripping of gas from galaxies will occur near the galaxy, and likely would appear as if it was hosted by that galaxy (Sun, Donahue & Voit 2007; Sun et al. 2010). Indeed, the intracluster light observed to date has been universally old (Zibetti et al. 2005). So, it is reasonable to assume that there exist no ‘prompt’ SN in the intragroup mass, particularly since we are here after a robust upper limit on the diffuse stellar mass. Thus, we can conclude that the diffuse component hosts at most 22 ‘delayed’ SN, and we can use the relation found above that one ‘delayed’ SN arises from a stellar mass of $6.62^{+3.92}_{-3.54} \times 10^{13} h^{-1} M_{\odot}$, to see that the total stellar mass in the diffuse component is $\leq 1.46^{+0.86}_{-0.73} \times$

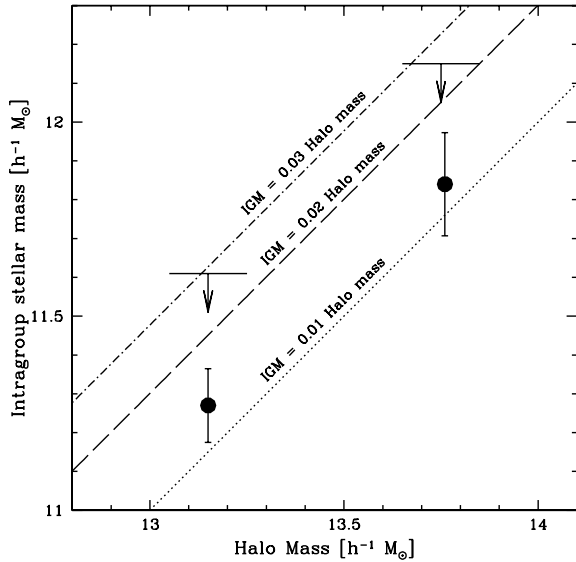


Figure 2. The measurements of intragroup stellar mass for our sample, assuming no prompt component of SN. The thick black line with the arrow represents our upper limits, while the dots are the best estimate after accounting for a contribution from possible host galaxies below the survey magnitude limit. Also shown are three equality lines where the intragroup stellar mass equals 0.03 (dot-dashed line), 0.02 (dashed line) or 0.01 (dotted line) of the total halo mass.

$10^{15} h^{-1} M_{\odot}$. Therefore, the total diffuse stellar mass per group is $\leq 1.04^{+0.61}_{-0.52} \times 10^{12} h^{-1} M_{\odot}$, or $\leq 2.69^{+1.58}_{-1.34}$ per cent of the halo mass, given the average halo mass per group of $3.86 \times 10^{13} h^{-1} M_{\odot}$. Taking the upper limit allowed by the statistical uncertainty, our robust upper limit on the fraction of total mass that occurs in the diffuse stellar component is 4.3 per cent. In Fig. 2, we show these upper limits in two bins of halo mass. We discuss the implications of this in Section 5.

4.2 Best estimate of the intragroup mass

We have presented a robust upper limit on the quantity of intragroup stellar mass in galaxy groups. We now attempt to make a more realistic calculation of the contribution from undetected host galaxies, to arrive at an estimate of the actual mass.

In the previous section, we assumed all 22 hostless SN were actually associated with the diffuse mass. However, three of these appear to be associated with photometric galaxies, which have inconsistent photometric redshifts. From their proximity to these galaxies, we think it is more likely that the photometric redshift is incorrect, and these are really ‘hosted’ SN, within the group. Moreover, we have argued that for typical groups up to 5 per cent of the group galaxy light is expected to be in unresolved hosts. Therefore, if stellar light scales as stellar mass, we would expect approximately two of the remaining 19 apparently hostless SNe to be ‘delayed’ SNe hosted in unresolved galaxies.

However, while the ‘delayed’ SN rate should only depend on the total stellar mass, galaxies which are strongly star forming will have a greater ‘prompt’ component than galaxies within our spectroscopic sample. To estimate this effect, we must adopt a scaling between the stellar mass and SFR. As low-mass galaxies are usually uniformly star forming, we assume that the low-mass galaxies double their stellar mass in a Hubble time (e.g. $\text{SFR} = \frac{M/M_{\odot}}{10^{10} \text{ yr}}$). Using

the relation of Dilday et al., we find that the number of prompt SN is equal to $9.3/2.8 = 3.3$ times the number of delayed SN, so that approximately six of the hostless SNe are likely due to ‘prompt’ explosions in unresolved galaxies. Taken together, this means that only ~ 11 of our hostless SNe are likely true intragroup SNe. Again, we assume that all true intragroup SNe are ‘delayed’ SNe, because the intragroup mass is uniformly old. Therefore, we can use the previous scaling which stated that one ‘delayed’ SN arises from a stellar mass of $6.62^{+3.92}_{-3.54} \times 10^{13} h^{-1} M_{\odot}$, to find that a total mass of $7.28^{+4.31}_{-3.89} \times 10^{14} h^{-1} M_{\odot}$ is in the diffuse component. On average, this corresponds to $5.20^{+3.08}_{-2.78} \times 10^{11} h^{-1} M_{\odot}$ per group, representing a fraction of $1.32^{+0.78}_{-0.70}$ per cent of the total halo mass. The black points in Fig. 2 show the final best estimate of the diffuse stellar mass in two bins of halo mass, after all the corrections discussed above. The diffuse stellar fraction is statistically indistinguishable in the two mass bins, with $\sim 1.3^{+0.73}_{-0.65}$ per cent in the lowest mass groups, and $1.2^{+0.62}_{-0.56}$ per cent for the more massive systems.

A potential systematic error in our results could occur if the SDSS SN pipeline and/or spectroscopic follow-up is biased towards finding SNe without hosts. The first issue, that of finding algorithm, was explored by Dilday et al. (2008), who found that the pipeline uncovers >98 per cent of SNe Ia to a redshift of 0.2. Even if the completeness were only 95 per cent and entirely biased toward hostless SN (i.e. assuming the 5 per cent missed SN are associated with galaxies), our result on the amount of mass in diffuse form would only change from 1.32 to 1.17 per cent. Regarding the spectroscopic follow-up, Sako et al. (2008) state that essentially all of the $z < 0.15$ SNe Ia were spectroscopically followed up, and our results are unchanged if we restrict just to this sample. Thus, we conclude that neither of these selection effects have a significant effect on our results.

5 DISCUSSION AND CONCLUSIONS

We have measured the diffuse stellar mass in galaxy groups using the rate of hostless SNe Ia. We find that $1.32^{+0.78}_{-0.70}$ per cent of the total halo mass of a group is in the form of this diffuse intragroup stellar mass. Although many numerical predictions exist for the mass of the diffuse intragroup material, they are usually stated as a fraction of the total stellar mass. To obtain this measure, we will use the stellar mass functions of Yang et al. (2009), which were measured for the same sample of groups we use. They find that the stellar mass function of the group galaxies is well approximated by a lognormal distribution for the central galaxy and a modified Schechter function for the satellite population. Integrating these functions over all galaxies reveals that the fraction of stars in galaxies is ~ 1.5 per cent of the halo mass for groups in our mass range.¹ Therefore, $\sim 47^{+16}_{-15}$ per cent of the stellar mass in our groups is in the diffuse component. This is significantly higher than the estimates of Purcell et al. (2007), who use Press–Schechter formalism along with analytic models for the disruption and stripping of haloes to estimate that ~ 20 per cent of the stellar mass is in a diffuse form. It is also significantly larger than that seen in the most massive clusters, which is more typically about 10 per cent (Zibetti et al. 2005).

In Fig. 3, we show the total stellar mass as a function of halo mass for our sample. This shows that, with the uncertainty, the total stellar fraction in our groups is $0.028^{+0.011}_{-0.010}$, with a robust upper

¹A very similar result is obtained if we use the total stellar mass within the spectroscopic sample, and include a small correction for the stellar mass below the spectroscopic limit.

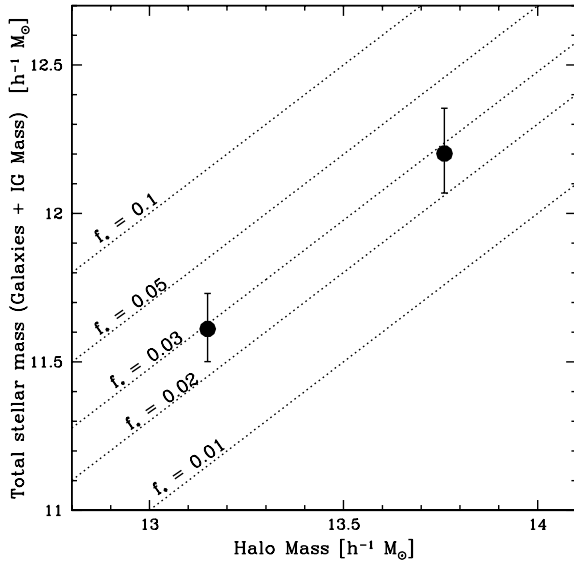


Figure 3. Total stellar mass in our sample of groups. This includes the diffuse intragroup mass measured in this Letter added to the stellar mass of galaxies in the same sample as determined by Yang et al. (2009). The dashed lines represent lines of constant total stellar fraction, $f_* = \frac{\text{Total stellar mass}}{\text{Total halo mass}}$. Our sample indicates the stellar fraction of these groups is $\sim 0.02\text{--}0.04$.

limit of 0.058. We find some tension with a previous measurement by Gonzalez, Zaritsky & Zabludoff (2007) of the stellar fraction in a few similar sized groups. They found ~ 6 per cent of the total halo mass was in some form of stars in these sized groups, while massive clusters have stellar fractions of only ~ 0.02 . Our robust upper limit on the stellar fraction is actually just consistent with their measurement, but this conservative limit would imply that there is almost three times as much stellar mass in the IGM as in the galaxies; not only is this almost certainly unreasonable, it is also much higher than Gonzalez et al. (2007) themselves find. In fact, the fraction of stellar mass we find in the IGM (~ 47 per cent) is in reasonable agreement with their study; the difference in our result is in the stellar mass fractions themselves, as evident in Yang et al. (2009). Since it is expected that clusters are formed from the buildup of groups (Berrier et al. 2009; McGee et al. 2009) and given that mergers do not destroy stellar mass, Balogh et al. (2008) showed that a group stellar fraction as high as found by Gonzalez et al. (2007) was incompatible with the low stellar fractions in clusters, and argued that the halo masses of the Gonzalez et al. (2007) groups were underestimated. The lower measurement of the group stellar fraction from this work and Yang et al. (2009) supports this conclusion.

We conclude, therefore, that despite the significant contribution from intragroup stars, the stellar mass fraction in groups is not significantly larger than in massive clusters. This suggests that the low gas fraction in groups (e.g. Vikhlinin et al. 2006; Sun et al. 2009) cannot likely be explained via an extraordinarily high star formation efficiency.

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