SPITZER 24 μm DETECTIONS OF STARBURST GALAXIES IN ABELL 851

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ABSTRACT

Spitzer-MIPS 24 μm observations and ground-based optical imaging and spectroscopy of the rich galaxy cluster Abell 851 at z = 0.41 are used to derive and compare star formation rates from the mid-IR 24 μm and from [O II] λλ3727 emission. Many cluster galaxies have star formation rates SFR(24μm)/SFR([O II]) ∼1, indicative of star formation in regions highly obscured by dust. We focus on the substantial minority of A851 cluster members where strong Balmer absorption points to a starburst on a 105–109 year timescale. As is typical, two types of galaxies with strong Balmer absorption are found in A851: with optical emission (starforming), and without optical emission (post-starburst). Our principal result is that the starforming variety, so-called ε(a) galaxies, are mostly detected (9 out of 12) at 24 μm—none of these we find typically SFR(24 μm)/SFR([O II]) ∼4. Strong Balmer absorption and high values of SFR(24 μm)/SFR([O II]) indicate moderately active starbursts (SB); both observations support the picture that ε(a) galaxies are the active starbursts that feed the post-starburst population. While 24 μm detections are frequent with Balmer-strong objects (even 6 out of 18 of the supposedly “post-starburst” galaxies are detected), only two out of seven of the continuously starforming ‘ε(c)’ galaxies (with weak Balmer absorption) are detected—for them, SFR(24 μm)/SFR([O II]) ∼1. Their optical spectra resemble present-epoch spirals that dominate today’s universe; we strengthen this association by showing that SFR(24 μm)/SFR([O II]) ∼1 is the norm today. That is, not just the amount of star formation but also its mode has evolved strongly from z ∼ 0.4 to the present. We fit spectrophotometric models in order to measure the strength and duration of the bursts and to quantify the evolutionary sequence from active to post-starburst. Our results harden the evidence that moderately active starbursts are the defining feature of starforming cluster galaxies at z ∼ 0.4.

Key words: galaxies: clusters: general – galaxies: evolution

1. INTRODUCTION

A remarkable change in our view of galaxy evolution over the last few decades has been the realization that the properties of galaxies are changing on relatively short timescales, in cosmic terms. The Butcher & Oemler (1978) effect, first at odds with the then-prevailing picture that strong galaxy evolution occurred only within the first few billion years, is now part of the orthodoxy—a large and still-growing body of evidence shows that the stellar populations and even the morphologies of many galaxies have undergone significant changes, even within the last four billion years. Butcher and Oemler’s discovery of a substantial population of luminous starforming galaxies in intermediate-redshift clusters—a great contrast with cluster populations today where only a small fraction of galaxies are still actively forming stars—is now widely confirmed and accepted.

Less well known, but likely as important for understanding the causes of the Butcher–Oemler effect, is the discovery by Dressler and Gunn (1983) that most of these starforming galaxies in the cores of distant clusters show a starburst signature in their optical spectra: both starbursts and post-starbursts are common. Later work has confirmed the ubiquity of this result (Couch & Sharples 1987; Wirth et al. 1994; Poggianti et al. 1999, hereafter P99; Tran et al. 2003).4 Data from these studies suggest that a significant fraction of field populations at z ∼ 0.5 is also undergoing moderate bursts of star formation (Dressler et al. 2004). This behavior contrasts with today’s population of field galaxies, for which continuous star forming is the dominant mode, and starbursts are rare. This is yet further evidence of rapid evolution of the galaxy population, at least as important, since it applies to field and cluster galaxies alike.

In this paper, we address one of the long-standing uncertainties of this subject—the amount of dust-obscured star formation that has not been generally accounted for in representative field and cluster populations at z ∼ 0.5. Although Balmer absorption is a reliable indicator of past starburst activity, a coherent picture requires evidence of the bursts themselves. This has been hampered by the possibility that much of the star formation is obscured by dust, and therefore not part of the tally made with optical-to-near-IR observations. The remarkable sensitivity of the Spitzer Space Telescope with its 24 μm MIPS camera is allowing great progress in removing this uncertainty.

As part of a successful Spitzer program to observe two rich clusters of galaxies, we investigated archival MIPS data for Abell 851, a cluster that is well studied in the optical, X-ray, and radio, and for which a significant spectroscopic sample has been obtained and explored in a companion paper (Oemler et al. 2009, hereinafter Oem09). Our purpose here is limited to spectra, after determining the “noise” from the Hαdistribution in their full sample. Dressler et al. (2004) show that the detections were in fact reliable—and the noise greatly overestimated—due to a difficulty with the bandpass measurement technique, which for small Hα-equivalent width returns negative values—see also Prochaska et al. 2007.
the implications for the amount and character of star formation in distant clusters, specifically the subject of “starburst versus continuously starforming” for distant galaxies. Issues of causes and mechanisms are beyond the scope of this paper, but Spitzer data for additional rich, distant clusters and their surrounding field populations will be able to advance these discussions considerably.

The paper is organized as follows. In Section 2 we lay out the issues, in Section 3 we address the ability of mid-infrared imaging to add to our knowledge of the star formation rates of distant galaxies, in Section 4 we present the optical and mid-IR data for A851, and in Section 5, we give the results of combining these data sets. In Section 6, we compare our detections of dusty starbursts in A851 with similar observations of present-epoch spirals. Finally, in Section 7, we apply stellar population models to the optical spectra + MIPS data and discuss the results in terms of a consistent picture of the starburst activity in distant clusters.

2. WHERE ARE THE STARBURSTS THAT FEED THE POST-STARBURST POPULATION?

Dressler & Gunn (1983) first reported spectra of L* galaxies in distant clusters with strong Balmer absorption but no emission lines and interpreted these as post-starburst (see also Couch & Sharpes 1987, P99). The question “where are the active starbursts that turn into post-starburst galaxies?” was largely set aside. Dressler et al. (1985) noted only a few examples in CL0024+24 of nearly pure emission-line spectra—characteristic of today’s strong starbursts, for example, Markarian galaxies. But, because it was expected that the starburst phase would be short, $\tau \lesssim 10^8$ yr, compared to the $\tau \sim 10^9$ yr that the galaxy would be recognized as post-starburst, it was reasonable at first to expect to catch few of the actual starbursts. This explanation became untenable as the Morphs study of 10 clusters accumulated more than 100 post-starburst spectra: although some tens of emission-dominated spectra were identified, their distribution was distinctly shifted to lower luminosities than the post-starburst galaxies (PSB)—the predecessors to the post starbursts would be, if anything, more luminous (P99).

However, the larger Morphs sample provided an alternate explanation. In addition to the post-starbursts, the Morphs sample included a substantial number of galaxies with strong Hα and (relatively weak) [O ii] emission. Initially, these were interpreted as decaying starbursts—a phase of subsiding star formation between the main burst and the post-starburst phase. However, the dusty appearance of many of these ‘e(a)’ galaxies (‘e’ for emission, ‘a’ for A-stars) led P99 to another explanation—that the e(a) galaxies were, in fact, the actual starbursts. If heavily obscured by dust, [O ii] emission would greatly under-represent the star formation rate. As examples, P99 pointed to the Liu & Kennicutt (1995) sample of present-day mergers, which shared the spectral properties of the e(a) galaxies (see Poggianti & Wu 2000, Poggianti et al. 2001). Liu & Kennicutt showed, from IRAS mid-IR observations and optical imaging, that the majority of star formation in such systems is hidden by dust from optical or near-IR observation. Detection with the VLA of a radio continuum of many of these putative dusty starbursts in the distant cluster sample also supported the idea of hidden star formation (Smail et al. 1999). Furthermore, radio detections of a few supposedly PSB galaxies suggested that dust might be hiding continuing star formation in some of these as well.

Subsequent work has been supportive of the identification of dusty starbursts in distant clusters. ISOCAM contribution to the study of mid-IR emission from present-epoch galaxies at all types was extensive. In particular, Duc et al. (2002) and Fadda et al. (2000) made pioneering observations of galaxies in clusters at $z \sim 0.2$. ISOCAM was not sufficiently sensitive to detect average star forming galaxies at $z \sim 0.5$; even at $z \sim 0.2$ more detections were of luminous infrared galaxies (LIRGs). Despite limited sensitivity, several studies detected luminous, dusty starbursts in clusters at these redshifts, galaxies that are rare (at best) in rich clusters at $z = 0$. The pre-Spitzer era of mid-IR emission from galaxies is well and thoroughly reviewed by Metcalfe et al. (2005).

Now, with MIPS on Spitzer, it is possible to measure star formation rates $\sim 1M_{\odot}$ yr$^{-1}$ at $z \sim 0.5$, a value typical of normal spiral galaxies today. This means that L* galaxies with even modestly elevated rates of star formation compared to today’s spirals are detectable, allowing us to test directly the claim by the Morphs that the e(a) galaxies in intermediate-redshift clusters are dusty starbursts of sufficient luminosity to feed the post-starburst population and judge, as well, whether the PSB galaxies are really post-starburst.

Ours is not the first study to use MIPS on Spitzer to image intermediate-redshift clusters. Geach et al. (2006) targeted two clusters at $z \sim 0.5$ and found many mid-IR sources in one, although comparatively few in another cluster of similar richness. They describe the properties of the population—luminosity function, spatial distribution, etc., but do not analyze the properties the individual galaxies and basically bypass the question of starbursts, consistent with the paradigm favored by Geach et al. in which starforming galaxies falling into clusters are simply extinguished.

Bai et al. (2007) and Marcillac et al. (2007) imaged two very rich clusters at $z \sim 0.8$, for which they detected 30 plus galaxies in the mid-IR that are either confirmed or suspected (photometric redshift) cluster members. Because of the greater distance relative to the Geach et al. clusters and A851, the detected galaxies have greater rates of star formation—tens of solar masses per year—most of these can be classified as LIRGs. The optical spectra of these mid-IR detections argue that these galaxies are strongly star forming and considerably obscured by dust. Both Bai et al. and Marcillac et al., like Geach et al., analyzed the properties of the population, velocity kinematics, galaxy morphology, spatial distribution, particularly with respect to X-ray emission, colors, and luminosity distribution. In addition, Marcillac et al. investigated the correlation with optical spectral types—passive, starforming, and post-starburst, but their sample included only four galaxies that are candidates for active, dusty starbursts, of which three are detected in the mid-IR. Our goal in this and subsequent studies is to extend this comparison of optical spectra and mid-IR emission to typical starforming galaxies of lower luminosities, which will provide a fuller picture of the evolution of the cluster population, $L > 0.4L*$.

This study of A851 and the future observations we will obtain with Spitzer-MIPS will provide crucial data for understanding the star-formation history of galaxies that are involved in building intermediate-redshift clusters. The optical spectroscopy and photometry of such samples are missing information about dust obscuration that is necessary to this task; adding the Spitzer data provides such data. We will pay particular attention to the presence of Balmer absorption in our sample galaxies, highlighting the importance of starbursts in cluster evolution (see D99, P99 and references therein). Unlike the other studies of clusters...
with Spitzer-MIPS, we will concentrate on modeling the star formation history with the critical addition of the mid-IR data. Specifically, through basic stellar population models of the data, we will address the question of whether the distinctions we have drawn between continuously starforming, starbursting, and PSB galaxies are quantitatively consistent with the observations of intermediate-redshift cluster galaxies.

3. THE DATA

3.1. Basic Properties of the Rich Cluster of Galaxies Abell 851

The rich cluster Abell 851 (aka CL0939+4713) at \( z = 0.41 \) is one of the best-studied intermediate-redshift clusters and one of the clusters in which PSB galaxies were first identified (Dressler & Gunn 1992). A851 is among the most populous clusters known at its epoch and is also noteworthy because it appears to be in the process of assembly through the mergers of several subclusters. This is especially evident in X-ray observations (Schindler et al. 1998) where two prominent centers of emission are also centers of galaxy concentration.

Although A851 is unusually rich and dynamically active, its galaxy population is not qualitatively different from that of other rich clusters at \( z \approx 0.5 \), as shown by studies by the Morphs collaboration (Smail et al. 1997; Dressler et al. 1999; P99; D04; Oem09). The majority of its galaxies are red, passive elliptical and S0 galaxies, but A851 is also well represented in both types of galaxies with strong Balmer absorption: those without emission that are identified as post-starbursts, and those with emission that have been suggested to be dust-obscured, active starbursts that feed the post-starburst population (P99).

Oem09 studied an extended region \( R \sim 2 - 3 \) Mpc around the core of A851, including Hubble Space Telescope (HST) images and spectroscopy for both an extended square region and the remarkable filament that stretches further, to the northwest of the cluster. Oem09 found a substantial population of active starbursts and fewer PSB galaxies in the outskirts of A851, consistent with the idea that many of the starbursts are triggered well outside the cluster core, probably within the infalling groups from which the cluster is growing (P99, Treu et al. 2003, Moran et al. 2007). Oem09 also found another population of starbursts that appear to have been triggered by passing through the cluster core.

Oem09 also showed that the morphology–density relation for this cluster is well developed, even though it is, at \( z = 0.41 \), in a relaxed dynamical state. From the spatially extended sample, it appears that A851 is one of the most active clusters known in terms of star formation and starbursts, but that these differences are quantitative rather than qualitative, and likely the result of the very dynamic phase in which it is observed. A complete description of A851, the observations, and the implications for galaxy evolution in clusters can be found in Oem09.

3.2. Optical data and Spitzer-MIPS Observations

The optical data for this study include photometry and spectroscopy from Dressler & Gunn (1992) and the Morphs collaboration. HST WFPC-2 observations that cover a \( 3 \times 3 \) mosaic (480 arcsec square) are described in Smail et al. (1997) and Oem09. The morphological information from these images is mainly discussed in Oem09 and briefly referenced here, but these fields basically define the extent of the photometric and spectroscopic sample that we use here. The photometric data come from these HST frames and ground-based observations by Dressler & Gunn (1983). The spectroscopic data come from Dressler & Gunn and the Morphs collaboration (Dressler et al. 1997, D99); they are explained in more detail in Oem09.

The core of Abell 851 was mapped in 24 \( \mu m \) by MIPS in Spitzer GTO program 83 (PI: G. Rieke). The background level was 32 MJy/\( sr \), which is classified as “medium” by the SSC. The observation was done in Photometry Mode, with six cycles of half-frame–overlapping coverage, and individual exposure times of 30 s. The resulting exposure time per-pixel is 2685 s in a \( 5' \times 5' \) box centered on the cluster, and 900 s in two flanking boxes each \( 5' \times 2.2' \) in area. The online synchrotron self-Compton (SSC) tool SENS-PET estimates that these exposure times should have 5\( \sigma \) point source sensitivities of 70 and 120 \( \mu m \), respectively. At these depths, confusion noise from extragalactic sources becomes important.

The 24 \( \mu m \) images were reduced and combined into a mosaic using the data analysis tool (Gordon et al. 2005) with a few additional processing steps (Egami et al. 2006). Photometry at 24 \( \mu m \) was obtained by point-spread function (PSF) fitting using the DAOPHOT task allstar, as detailed in Rigby et al. (2008).

The areas covered by optical spectroscopy and MIPS 24 \( \mu m \) images are of similar size, but not entirely coincident. There are 101 cluster members with high-quality optical spectra (\( Q \leq 3 \); see Oem09 for more information). Of these, 83 have MIPS 24 \( \mu m \) coverage. Of these, 22 are Spitzer detections with 24\( \mu m \) > 80 \( \mu m \),Jy. Using a \( R = 1.4' \) matching radius, and given the number density of 24 \( \mu m \) sources, with \( f > 80 \mu m \),Jy in the image, we expect from the P-statistic (Lilly et al. 1999) that approximately one cluster member will be spuriously matched to a 24 \( \mu m \) detection with \( f > 80 \mu m \),Jy. For nondetections in the regions of deep and shallower coverage, we quote upper limits of \( f < 80 \mu m \),Jy and \( < 120 \mu m \),Jy, respectively. For nondetections located close to bright sources, we assign a larger upper limit of \( f < 200 \mu m \),Jy.

4. MEASUREMENTS OF STAR FORMATION HISTORIES FROM OPTICAL AND MID-IR DATA

4.1. Optical Diagnostics

In this study, we focus on the emission feature [O II] \( \lambda \lambda 3727 \) oxygen doublet and the Balmer absorption line \( H\delta \) as indicators of the star formation rate (SFR). As discussed in P99 and D04, these two features measure the time-averaged SFR over \( \tau \sim 10^7 \) yr and \( \tau \sim 10^9 \) yr, respectively. Measurements of [O II] and \( H\delta \) from our sample spectra have been done with a semi-automated line-fitting technique, described in Oem09.

A quantitative comparison of the strength of these indicators measures whether the star formation rate has been steady over the previous \( \tau \sim 10^7 \) yr or whether there has been a starburst with a rapid decline in the SFR over that timescale. An ongoing starburst is inferred by comparing the current \( (\tau \sim 10^7 \) yr) SFR to the total stellar mass of the galaxy through spectral synthesis modeling.

In the following, we use the strengths of [O II] and \( H\delta \) to divide galaxies into spectral types which correspond to different histories of star formation (see Oem09, Table 5 for the definition of the types); \( e(c)'s \) are galaxies with continuing star formation, \( k+a's \) and \( a+k's \) are moderate and strong post-starbursts, \( e(b)'s \) are starbursts with strong optical emission, \( e(a)'s \) are dusty starbursts with weak optical emission, \( k's \) are passive, early type galaxies, and \( e(n)'s \) are AGN’s. By starbursts, we shall mean any galaxy whose observed star formation rate is at least a factor of 2 higher than its long-term average. We shall use the term “post-starburst” to signify any galaxy which had a starburst in the
recent ($\tau \lesssim 10^8$ yrs) past, but at the epoch of observation shows no detectable star formation, and buried starburst to signify a starburst which is sufficiently obscured by dust to completely hide its [O II] emission.

Oem09 have measured the equivalent width of [O II] in the A851 sample. We convert these equivalent widths to [O II] luminosities by the following steps. (1) Because our optical spectra cover only a fraction of each galaxy, while the Spitzer photometry covers the entire object, we must make some assumption about the distribution of [O II] flux over the face of the galaxy. In the absence of any other information, we assume that the [O II] flux has the same distribution as the visible light. (2) Using the total $r$ magnitudes of the galaxies, we calculate the total $F_r$ at 6500 Å. (3) Using the shape of our fluxed spectra, we then determine the total $F_{\alpha}$ at 3727 Å, and from this and the measured EW([O II]), we calculate the total flux in the [O II] line. (4) We then use a standard $\Lambda$ cosmology to calculate total [O II] luminosity. This method is dependant on our assumption about the spatial distribution of [O II], but the spectra, which come from slits that typically cover $\sim 8 \times 12$ kpc at $z = 0.41$, sample a reasonable fraction of each galaxy in our sample, so the sensitivity of our result to this assumption is probably not severe.

The UV flux from young, massive stars in H II regions ionizes oxygen atoms which then produce [O II] through recombination. Only the hottest stars have sufficient UV flux to contribute, so [O II] flux in an H II region is due mainly to the population of O and B stars. Rates of star formation come from folding in the well-known lifetimes of these stars. Deriving the SFR for stars of all masses requires the adoption of a universal initial mass function—an often-questioned, but yet to be invalidated, assumption. We have employed Kennicutt’s (1998) prescription:

$$SFR = \frac{M_\odot}{yr^{-1}} = 1.4 \times 10^{-41} L([\text{O II}]) \text{ ergs s}^{-1}. \quad (1)$$

We note that, because this is an average rate that includes lower luminosity spiral and irregular galaxies less luminous irregular galaxies, we are perhaps overestimating the SFR for our sample—by $\lesssim 40\%$—which makes this a conservative choice for the purposes of this study. On the other hand, there might be even greater uncertainty just from using this $z \sim 0$ relation on earlier epoch starforming galaxies. We show below that, despite these uncertainties, we derive approximately equal SFRs from both the Kennicutt [O II] relation and from 24 $\mu$m for “normal” starforming galaxies (in both A851 and a present epoch field sample covering the same luminosity range), which is reassuring.

The Kennicutt formulation is sometimes corrected for dust extinction and sometimes not. The relation adopted here is corrected for average dust extinction from [O II] to H$\alpha$, but not for extinction at H$\alpha$. Our goal is to compare the SFRs derived from [O II] to the SFR derived from the dust-insensitive 24 $\mu$m luminosity, so measuring [O II] flux and applying the standard correction to H$\alpha$ for present epoch galaxies will show whether the distant starforming galaxies in A851 have an unusual amount of dust and thus more star formation than is evident with optical diagnostics. Because our analysis depends on the relative values of these two indicators, our conclusions are not dependent on a rigorous analysis of the absolute value of extinction in our sample galaxies, which is beyond the scope of this paper.

Measurements of H$\alpha$ strength are comparatively insensitive to dust absorption, because, over the $10^8$ yr timescale for which it measures the SFR, the A–F stars that contribute most to the H$\alpha$ signal are expected to have diffused out of the dusty regions in which they were born.

4.2. Mid-infrared diagnostic

Empirically, the total infrared (8–1000 $\mu$m) luminosity, L(TIR), correlates reasonably well with other star formation rate tracers in nearby dusty star-forming galaxies (Hunter et al. 1986; Lonsdale et al. 1987). Far-IR emission arises from graybody emission of dust heated by hot stars. Since the escape fraction for ionizing photons is low, and the dust cross-section peaks in the UV, the far-IR is essentially a calorimeter of hot young stars (Kennicutt 1998, and references therein). Only at low redshift is it possible to fully sample the long-wavelength spectral energy distribution (SED) in order to measure a galaxy’s L(TIR) directly. Fortunately, monochromatic luminosities in the rest-frame mid-IR (5–30 $\mu$m) range correlate well with L(TIR) at low redshift (Chary & Elbaz 2001, Calzetti 2007), and this correlation has been demonstrated to extend to $z = 1.3$ (Marcillac et al. 2006).

Mid-IR emission is a combination of continuum from small grains plus aromatic features. The luminosity surface density in both the continuum-dominated $\lambda_v = 24 \mu$m spectral region and the aromatic-dominated $\lambda_v = 8 \mu$m spectral region correlate well with that of extinction-corrected Paschen$\alpha$ (Calzetti 2007); in both cases, the $\sigma$ scatter is about 0.3 dex. Figure 3 of Alonso-Herrero et al. (2006) shows a tighter correlation between rest-frame 12 $\mu$m and extinction-corrected Paschen$\alpha$, $\sigma \sim 0.1$–0.2 dex.

At $z \sim 0.4$, the 24 $\mu$m band of MIPS on Spitzer detects rest frame 15–19 $\mu$m. These wavelengths are also dominated by continuum emission from small grains, with a contribution from the relatively weak 17 $\mu$m aromatic feature. The rest-frame 15–19 $\mu$m bandpass has not been similarly calibrated at $z = 0$, because IRAS had no such band; however, since the 15–19 $\mu$m continuum arises from the same small grains that produce the 12$\mu$m and the 24$\mu$m rest-frame continua, the scatter in this band should be similar. We conclude from the results from Calzetti (2007), Marcillac et al. (2006, 2007), Alonso-Herrero et al. (2006), and Smith et al. (2007) that the continuum emission in this region should trace the star formation rate with only moderate dispersion. Because mid-IR photons are not further absorbed by other dust grains in star-forming regions, they provide a clear view of the total star formation in the system, which [O II] and even H$\alpha$ cannot do.

In the following section, we will use template SEDs generated by Chary & Elbaz (2001) and Dale & Helou (2002) that model the flux distribution from the mid-to-far IR to derive the total SFRs for our detected galaxies. The SED shapes of these templates vary smoothly as a function of mid-IR luminosity, allowing a reliable correction to bolometric IR emission from observations over a relatively narrow wavelength range. A small complication is that these templates do not include $\lambda > 15 \mu$m aromatic features. This means that the 17 $\mu$m aromatic feature, which falls in the 24$\mu$m band at the $z = 0.407$ redshift of A851, will not be correctly accounted for. However, the feature has a typical equivalent width of only 0.36 $\mu$m (Brandl et al. 2006), and affects the detected MIPS 24 $\mu$m flux density only at the 10% level. This small systematic effect is not important for our results.

For a sample of 59 SINGS galaxies, Smith et al. (2007) observed an intrinsic dispersion in aromatic feature strength compared to the dust continuum. Figure 19 of Smith et al. quantifies how this spectral variation affects 24 $\mu$m flux density: at $z = 0.4$ the 10%–90% variation in the spectra of their
luminous \((L(\text{TIR}) > 2.6 \times 10^{10} L_\odot)\) sample causes a \(\pm 20\%\) change in the MIPS 24 \(\mu m\) flux density. Thus, flux differences of this magnitude should not necessarily be interpreted as differences in star formation rate, since they may be due to intrinsic spectral variation.

Despite these caveats, the robustness from dust obscuration, the well-behaved nature of the mid-IR continuum (Calzetti 2007), and the relative weakness of the 17 \(\mu m\) aromatic feature makes flux density a reliable diagnostic of star formation rate in bursting galaxies.

4.3. Deriving Star Formation Rates From Mid-IR Fluxes.

We converted from observed 24 \(\mu m\) flux density to inferred star formation rate as follows. Chary & Elbaz have derived template SEDs that model the full emission from 8–1000 \(\mu m\) for galaxies with a wide range of mid-IR luminosity. We transformed each of the Chary & Elbaz synthetic templates to the cluster redshift and converted \(L_\lambda\) to \(f_\lambda\), assuming a flat cosmology with \(h_0 = 0.72\) and \(\Omega_\Lambda = 0.73\). We then computed the 24 \(\mu m\) flux density that would be measured for this template using the MIPS response curve.\(^5\)

We integrated each template from the rest-frame 8–1000 \(\mu m\) to find the total infrared luminosity, and converted that to a star formation rate using Equation (4) of Kennicutt (1998). The result is a look-up table, at the cluster redshift, of star formation rate as a function of 24 \(\mu m\) flux density. For the range of detected MIPS flux densities, the corresponding Chary–Elbaz templates were numbers 36–75.

This extrapolation from the rest-frame 15–19 \(\mu m\) to total 8–1000 \(\mu m\) luminosity necessarily depends on the templates assumed. Since we observe large populations of A stars extending well beyond the star-forming regions in galaxies which, we will show, have had significant, long-duration starbursts, we considered the extra heating that these might provide. Our modeling included comparing the contribution to mid-IR luminosity from young populations (\(\tau \lesssim 10^7\) yr) to intermediate-age populations (\(\tau \sim 10^8\) yr). From this, we concluded that, for a Salpeter IMF and a single-age Starburst 99 model (Leitherer et al. 1999), the power available in A stars to heat dust is only \(\sim 1\%\) of the power available from O and B stars. Thus, we expect our 24 \(\mu m\) detections to be dominated by O and B stars, even in galaxies with large A star populations.

5. RESULTS

5.1. Detection with Spitzer-MIPS is a Strong Function of Spectral Type

In Figure 1, we show the result of our attempt to measure Spitzer 24 \(\mu m\) flux densities for our A851 cluster sample. We plot Spitzer 24 \(\mu m\) flux density versus \(R\)-band optical flux for the 96 confirmed members of A851 (see Oemler et al. 2009) that are within the Spitzer field. Figure 1 shows that—even for cluster members, which comprise an essentially volume-limited sample—galaxies are detected over a wide range of luminosity. In other words, we are not picking off only the most luminous objects. Most of the cluster members are not detected; however, this sample includes many galaxies that are not star-forming (passive), for which detection by Spitzer at 24 \(\mu m\) is not expected, unless the galaxy harbors an AGN.

The nondetection of galaxies without star formation is seen more easily in Figure 2, from the data in Table 1 which break down the detections by optical–spectral classification. Of the 41 passively-evolving ‘k’ type galaxies, only two are detected. There is nothing in the optical spectra of these galaxies that suggests any activity. It is possible that they could be examples of extremely dust-hidden star formation, as we find below for some of the putative PSB galaxies, or AGN, or both.

5.2. Continuously Starforming (“normal”) Galaxies are Generally Not Detected

Our A851 cluster sample includes both continuously star-forming (CSF), e(c) galaxies in addition to starburst (SB) and post-starburst galaxies (PSB). The strength of Balmer absorption lines in an integrated spectrum of a galaxy is key to distinguishing the CSF galaxies from the SB and PSB galaxies. The Balmer absorption line strength is a combination of effects, including (1) the dominance of Balmer absorption lines in the spectra of A stars, which contribute most of the light in populations of age \(\tau \lesssim 10^7\) years; (2) the in-filling of Balmer emission from the ionized gas in \(H\ II\) regions excited by OB stars; (3) the migration of A stars from the dust-obscured \(H\ II\) regions of their birth, and

\[^5\]http://ssc.Spitzer.caltech.edu/mips/spectral_response.html.
the distribution and amount of that dust; (4) the strength and duration of the starburst; and (5) the relative contribution of light from KIII stars—populations older than $2 \times 10^9$ years. It is the combination of these effects that results in substantially different spectra for CSF as compared to SB or PSB galaxies, the key to distinguishing CSF galaxies from other types.

The part of the A851 cluster sample that is coincident with Spitzer MIPS observations contains seven CSF e(c) galaxies. Only two of these are detected with MIPS. The seven e(c) galaxies cover the full range of optical and 24 $\mu$m luminosity, so this poor detection rate is not mainly due to some luminosity-dependent selection effect. As we show in Section 6, we expect SFR(IR) $\sim$ SFR([O II]) for these galaxies (from a comparable low-redshift, local sample), which would give them 24 $\mu$m luminosities scattered around the Spitzer–MIPS detection limit.

5.3. One-third of Post-starburst Galaxies are Detected

The PSB galaxies of types “k+a” and “a+k” are also mostly undetected, but the fraction 6/18 that are detected is significantly higher than even that of the e(c) galaxies, so this is a surprisingly high rate for galaxies that are supposed to be observed after star formation has completed. The fact that some of these PSB galaxies could have substantial star formation hidden by dust, particularly in their nuclei, had been previously suggested by detections in the radio continuum (Smail et al. 1999), preferentially of objects with the strongest H$\delta$. These a+k galaxies also show the broadest H$\delta$ absorption lines, indicative of the youngest A-star populations (closest in time to the burst)—see D04 and Oem09. Of the a+k galaxies in the Spitzer field, 2/5 are detected, compared to only 4/13 of the k+a, but with such a small sample, this is only suggestive.

The Spitzer data, then, lead to two important results for the post-starbursts. (1) Most of the galaxies classified as post-starburst are exactly that—there is little or no ongoing, hidden star formation (SFR $< 3$ $M_\odot$ yr$^{-1}$). This removes a critical uncertainty in earlier work. (2) A significant minority of cluster galaxies classified as post-starburst hide some residual star formation. A few of these may be as active as the starbursts we discuss next, but as we show in Section 7 (where we model the history of star formation), for most the rate of residual star formation is much lower than the preceding burst. It is quite possible that this remaining dust-obscured star formation is concentrated to the center of the galaxy—this is perhaps the only location where a very high extinction can be supported—while the previous, larger starburst might have been a more global, and thus more powerful event.

5.4. Candidate “Active Starburst” Galaxies—the Majority are Detected!

As explained in Section 2, our hypothesis has been that e(a) galaxies, which show both strong H$\delta$ and some [O ii], are active starbursts that feed the post-starburst population. Because the [O ii] strength of these systems is insufficient to indicate a starburst, this only makes sense if most of their star formation is hidden by dust. The Spitzer 24 $\mu$m data for A851 confirm that hypothesis—for this cluster, at least. For the e(a) galaxies, 9/12 are detected.$^6$ This is our major result.

To quantify what this means for the amount of star formation that has been dust-obsured, we calculate independently SFRs from [O ii] and 24 $\mu$m, as described in Sections 4.1 and 4.2. Because there is considerable uncertainty in the measurements for each individual galaxy (the calibrations will depend on average values of dust temperature and UV-excitation by young stars, for example), we show in Figure 3 the result of this comparison as a cumulative distribution of SFRs for both indicators. We plot only the galaxies for which [O ii] is detected, [O ii] $\leq -4$ Å $+$. The upper panel is for weak H$\delta$ absorption, what we identify as CSF—spectral type e(c)—starting at $1 M_\odot$yr$^{-1}$ in the upper right corner and proceeding to very high rates of star formation for a few galaxies in the 10’s of $M_\odot$yr$^{-1}$. The solid points show the rates inferred from the [O ii] indicator, the open circles, the 24 $\mu$m indicator. The fact that the two lines closely follow each other means that approximately

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$^6$ This includes two galaxies that we detected in [O ii] with an equivalent width of [O ii] $\sim 4$ Å $+$. This would have placed them in the k+a category previously, but in the context of studying SFR from [O ii], it makes more sense to include them as e(a) galaxies here, because their weak [O ii] flux is the result of extinction, not a low star formation rate.
Because of the inclusion of a partial extinction correction in the Kennicutt relation for SFR([O ii]), SFR(24 μm)/SFR([O ii]) ∼ 1 occurs at an extinction of about 0.9 mag at [O ii], calculated for a foreground screen (see Kennicutt 1998). Equality of these two derived star formation rates does not mean that star formation is completely unobscured, but is attenuated by dust as is typical for a present-epoch spiral galaxy.

Figure 3. Cumulative distributions of star formation rates (SFRs) for the galaxies in A851 measured from Spitzer 24 μm fluxes and [O ii] emission lines. The data are for all galaxies with EQW([O III]) < −4 Å. Galaxies in which EQW(Hδ) < +4 Å—e(a)—are shown in the upper plot; galaxies with Hδ > +4 Å—e(b)—are shown on the bottom. The weak Balmer absorption of the upper sample is indicative of normal, continuously star-forming galaxies, while the bottom is a sign of starburst activity. The line with open circles shows the cumulative distributions of SFRs derived from [O ii], and the line with solid points shows the distribution with SFRs derived from 24 μm. The lines trace each other in the upper plot—both methods measure the same SFR, but in the starbursts of the lower plot show an offset that corresponds to a factor of 4 greater SFR(24 μm) compared to the SFR([O ii]). In other words, starburst galaxies—identified by Hδ absorption—have a majority of their star formation obscured by dust, while continuously star-forming galaxies do not.

6. COMPARISON WITH LOCAL SAMPLES OF STARFORMING GALAXIES

Based on the [O ii] and Hδ spectral indices, P99 and D04 have argued that moderate starbursts—like those in A851 we are discussing here—are a common feature of the intermediate-redshift galaxy population, both cluster and field. The Spitzer–MIPS data for A851 give us an opportunity to investigate this claim and remove the uncertainty of dust-obscured star formation to which the optical indicators are more prone. In order to demonstrate that the prevalence of dust-obscured starbursts at z ∼ 0.4 is an epoch-dependent effect, we need to compare to a like sample of star-forming galaxies at the present epoch. Do present-epoch star-forming galaxies mostly have SFR([O ii]) ∼ SFR(IR), indicating that the modest extinction assumed in deriving SFR([O ii]) applies? Or, do many of them have a majority of their star formation hidden by dust, so that SFR(24 μm) >> SFR([O ii])?

Despite the proliferation of local galaxy surveys, constructing a local comparison sample is not easy. To begin with, we cannot use present-epoch rich clusters as a source, since these contain very few star-forming galaxies of mass M > 10¹⁰ M☉; this is the Butcher–Oemler effect, the point at which we started. We must instead use galaxies in the field—isolated and in groups—to judge if the characteristic mode of star formation, as well as its amount, has changed over time.

Another difficulty is that we need both 24 μm observations and [O ii] fluxes to cover the full disk of each galaxy in order to correspond to the distant cluster data. The survey that comes closest to this is a study of 417 star-forming galaxies by Moustakas & Kennicutt (2006). In this study, [O ii] fluxes were obtained from observations for which the slit of the spectrograph was scanned across the galaxy in order to obtain an integrated [O ii] flux, as we obtain by necessity for intermediate-redshift galaxies by using ∼ 1 arcsec-wide slits. Unfortunately, this survey is not volume limited, but rather it was chosen to represent many different galaxy types: not only normal galaxies, but also starbursts, peculiar galaxies, interacting/merging systems, and dusty, infrared luminous galaxies were handpicked for inclusion. As a result, we were not able to use this study to assemble a sample, based on optical luminosity alone, that was complete in any volume-limited sense.

However, the Kennicutt–Moustakas survey provides data that do allow us to construct such a sample. In Figure 4, we show total U-band flux vs integrated [O ii] flux for all galaxies from that survey for which both measurements are available. Fluxes are from the tables of Moustakas & Kennicutt (2006), which for U-band is generally taken from RC3 (de Vaucouleurs et al. 1995), and correspond to total magnitudes, that is, photometry through fixed apertures has been used to extrapolate a total brightness for the galaxy in the U-band. The strong correlation is due to the fact that the UV flux arises from the hot young stars that power [O ii] emission from the H ii regions. Even with the ambiguity of dust absorption/obscuration, the fact that these two indicators arise from the same spatial regions assures a good correlation. From the data in Figure 4, we fit a relation between integrated U-band photometry and integrated [O ii] emission, so that we can use U as a proxy for OIII:

\[
\log L([O ii]) = M(U\text{-band})/ -2.5 + 32.8404 \tag{2}
\]

Next, we construct a volume-limited local sample of galaxies using the NASA/IPAC Extragalactic Database (NED), as follows. We use an “Advanced All-Sky” NED query, restricting the velocity to 1000 km s⁻¹ < v < 2500 km s⁻¹, and select the 241 galaxies with absolute magnitude M_V < −19.5. We remove galaxies whose morphological type is listed as E or S0.8

This large percentage reflects the prominence of the Virgo Cluster.
we find the local sample to cluster around SFR(IR)/e(a) galaxies in A851, those identified as starbursts. Rather, SFR(IR) in SFR(IR) galaxies without starbursts. There appears to be a rising trend 1, values that we found for the e(c) galaxies in A851—\( \sim \) SFR—about the absolute magnitude distribution of our A851 sample, for local galaxies corresponding to the absolute magnitude distribution of our A851 sample, \(-22 < M_V < -19.5\), we find that, on average, the SFR(IR) \( \lesssim \) SFR(U). That is, we find few galaxies comparable to the SFR(IR)/SFR([O ii]) \( \sim 4 \) that we found to be typical of the e(a) galaxies in A851, those identified as starbursts. Rather, we find the local sample to cluster around SFR(IR)/SFR(U) \( \sim 1 \), values that we found for the e(c) galaxies in A851—galaxies without starbursts. There appears to be a rising trend in SFR(IR)/SFR(U) for the faintest objects in the local sample, but the IRAS sensitivity limits begin to be important, and these are, at any rate, fainter than the galaxies in our A851 sample. As we suggested earlier, finding SFR(U) \( \approx \) SFR(24 \( \mu \)m) for the large local sample and the relatively small e(c) sample in A851 supports the claim that we are dealing with the same kinds of objects, and it also indicates that our 24 \( \mu \)m SFR diagnostic is reasonably good.

From our small but complete sample, we can see that for typical, present-epoch, star-forming galaxies, star formation is only moderately obscured by dust. While it is not hard to find galaxies that are significantly dust-obsured today, they account for only a few percent of the local population (see, for example, Rieke & Lebofsky 1978). For the Morphs 10-cluster sample, Dressler et al. (1999) found a typical fraction of e(a) galaxies of 10–20%. Assuming the association of dusty starbursts with e(a) spectra, we find in A851 is representative of this larger sample, this points to a factor of \( \sim 4 \) decrease in the number of dusty starbursts in the last 4 Gyr, a relatively short time in cosmic terms.

7. THE STAR FORMATION HISTORIES IN A851 GALAXIES

The next step should be to analyze the spectra of our galaxies to see what the heuristic distinctions 'starburst, post-starburst, and 'continuously star-forming' really mean in terms of star formation histories. Our data for this study are minimal for this purpose, but here we develop the tools in anticipation of the much larger, higher quality data set to come. Our A851 galaxies have on-average low S/N spectra, so we follow the technique of Dressler et al. (2004) to increase the S/N substantially and create representative templates of each class. We use the spectrophotometric model of Fritz et al. (2007) to analyze the composite spectra in order to derive approximate star formation histories of the various classes. The model performs a simultaneous fit to the stellar continuum and to a number of emission and absorption features in each observed composite spectrum, as well as to the total IR luminosity, as derived by the 24 \( \mu \)m flux (Section 4.3). For the A851 composites, we substituted the broad-band fluxes in place of the optical continuum shape, due to uncertainties in the relative flux calibration of these spectra.

The program measures equivalent widths of absorption and emission features in the modeled, synthetic spectra in the

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**Figure 4.** U-band flux vs. [O ii] flux for the Moustakas & Kennicutt (2006) sample of local star-forming galaxies. The [O ii] spectra are unique in that the spectrophotograph was scanned over a large fraction of the galaxy. The solid line is the best-fit line of unity slope, with coefficients given in Equation (2); this relation lets U-band flux be used as a proxy for [O ii].

**Figure 5.** Comparison of U-band and 25 \( \mu \)m–derived star formation rates for the local volume–limited sample, using the [O ii] vs. U-band calibration (Figure 4). The typical luminous (\( M_V < -19.5 \)) star-forming galaxy in the local sample has SFR(IR)/SFR(U) \( \sim 1 \), in other words, the optical measurement of the star formation rate is consistent with the SFR determined from the mid-IR. This suggests that dust obscuration is moderate for a typical present-epoch spiral or irregular galaxies. Only a few galaxies show significantly enhanced SFR(IR)/SFR(U) \( \sim 3 \), indicative of a high level of dust obscuration, whereas the average SFR(IR)/SFR(25\( \mu \)m) \( \sim 4 \) for the distant galaxy sample with the starburst signature. Open symbols represent known AGNs, which are excluded because their mid-IR fluxes are not mainly a product of star formation. The errors in this plot are dominated by extrapolation to total U-band magnitudes, which are typically 20 less.

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\[ \log L(8–1000\mu m)/(L_{sun}) = 0.89942\ast(\log L_{\nu}^{25}(\mu m) + 1.77782) \]  
and from there to SFR using the relation from Kennicutt (1998).

To make the most straightforward comparison to the A851 sample, in Figure 5 we plot log SFR(IR)−log SFR(U) versus \( M_V \) for the local sample. For local galaxies corresponding to the absolute magnitude distribution of our A851 sample, \(-22 < M_V < -19.5\), we find that, on average, the SFR(IR) \( \lesssim \) SFR(U). That is, we find few galaxies comparable to the SFR(IR)/SFR([O ii]) \( \sim 4 \) that we found to be typical of the e(a) galaxies in A851, those identified as starbursts. Rather, we find the local sample to cluster around SFR(IR)/SFR(U) \( \sim 1 \), values that we found for the e(c) galaxies in A851—galaxies without starbursts. There appears to be a rising trend in SFR(IR)/SFR(U) for the faintest objects in the local sample, but the IRAS sensitivity limits begin to be important, and these are, at any rate, fainter than the galaxies in our A851 sample.

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From our small but complete sample, we can see that for typical, present-epoch, star-forming galaxies, star formation is only moderately obscured by dust. While it is not hard to find
same way as is done for the observed spectrum. This requires that, in performing the fit, spectra representing a single-stellar population, or SSP, are degraded to the resolution of our observed spectra, and also that spectral regions with sky-subtraction problems are excluded. The result is a sum of single-stellar populations (SSPs) that minimize a $\chi^2$ function that measures the differences between the model and the observed values of the observables. The fitting algorithm is discussed in detail in Fritz et al. (2007).

Dust obscuration is allowed to vary with stellar age to account for the fact that younger stars are generally more obscured than older ones. Three metallicities—solar, $Z = 0.05$, and $Z = 0.004$—are explored when searching for the best fit. For each value of SSP metallicity, we perform 11 different fits of the same observed spectrum, changing both the initial point in the parameter space and the seeds of the random number generator, to evaluate the robustness of our results and the “spread” in parameter space (i.e., in star formation history) of all acceptable solutions. We choose the metallicity yielding the best $\chi^2$. Among the 11 models of that metallicity, we choose as reference model the one that has the median value of the total stellar mass: all the quantities quoted in this paper, such as masses, star formation rates, and extinction values, refer to this model. Error bars are computed as the half-difference between the two models (among the 11) with the most disparate values of total mass from the reference model. Details on the error determination for the SFRs computed by our model can be found in Fritz et al. (2007). The model employed here uses the new MILES observed stellar library from Sánchez-Blázquez et al. (2006) and a Salpeter IMF with stellar masses in the range $0.15 \leq M / M_\odot \leq 120$.

Finally, since not all galaxies are detected by Spitzer-MIPS, we explored two cases: one in which the nondetections correspond to an IR luminosity $= 0$, and one adopting as IR emission the upper limit of our Spitzer data, $SFR = 3 M_\odot$ yr$^{-1}$. These two cases should bracket the possible range of star formation rates acceptable, and allow us to assess the uncertainty in the conclusions due to the unmeasured IR fluxes.

By determining the contribution of SSPs of different ages, the model yields a star formation history. That is, the mass formed at each cosmic time up to the epoch of observation, the extinction by dust and the total stellar mass for each composite spectrum. The synthetic spectra computed by the model are compared to the input composite-spectra observations in Figure 6. In the following sections, we discuss each of these classes and the SFR histories that have been derived.

### 7.1. Post-starburst Spectra

Post-starburst spectra with and without a Spitzer–MIPS detection have been modeled separately in order to compare their star formation histories. In the following discussion, we will use the term “observation epoch”—OE—to refer to the properties of galaxies as observed at the lookback time, for this case, approximately 4 Gyr ago.

The Spitzer-detected, post-starburst (k+a) composite spectrum is best fitted by a population of age $\tau > 6 \times 10^7$ yr that comprises 70% of the OE galaxy stellar mass, followed by a strong burst occurring over $2.5 \times 10^8$ yr before OE that produced most of the remaining 30%. The IR detection by itself indicates residual continuing star formation at the OE (Figure 7). The average galaxy stellar mass for this type was $M = 1.50 \times 10^{11} M_\odot$. The average SFR per galaxy was about $16 M_\odot$ yr$^{-1}$ over the galaxy’s history, but during the last $\tau \lesssim 6 \times 10^8$ yr, the SFR was considerably higher, $72 M_\odot$ yr$^{-1}$. More recently, over the last $2 \times 10^7$ yr before OE, the rate was $9–10 M_\odot$ yr$^{-1}$, significant in absolute terms, but substantially less to the extended high rate of star formation that preceded it. To summarize in words, the IR-detected PSB galaxies are galaxies that have experienced a substantial burst of star formation—significantly above the long-term past average—followed by a level of ongoing star formation that is significant in absolute terms, but a sharp decline from the previous burst.

Our model for the IR-undetected post-starburst (k+a) spectrum confirms a substantial burst that is followed by a low-to-zero level of residual star formation (depending on how the IR nondetections are handled). The average SFR per galaxy in this group is $\sim 12 M_\odot$ yr$^{-1}$ over the typical galaxy’s history, rising by a factor of $3.3 (1.4)$ to $39 (17) M_\odot$ yr$^{-1}$ (the first number corresponds to setting IR flux $= 0$, while the number in parentheses corresponds to setting the IR flux $= $ upper limit) during the last $6 \times 10^7$ yr, and $0.0 (0.9)$ solar masses per year during the last $2 \times 10^7$ yr. In words, the burst of star formation represents a significant rise over the past average, and there is no significant star formation at the epoch of observation—a definite post-starburst.

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9 Though the equivalent widths of the spectral features and the broad-band continuum fluxes can be reproduced, our model fails to account for the broadness of the Balmer lines in Spitzer-detected a+k/k+a, as can be seen in Figure 6 (second spectrum from the top). We found no single SSP or combination that was able to account for this. We simulated the effects of a high velocity dispersion of 250 km s$^{-1}$ for the galaxy, by convolving our SSPs with a Gaussian. The top spectrum of Figure 6 shows the best fit star formation history and rate unchanged with respect to the unBroadened fit, however, the line width is now reproduced. The broadening of the lines due to high galaxy velocity dispersions is consistent with the high average galaxy stellar mass found by both types of fits, $M = 1.5 \times 10^{11} M_\odot$. This mass agrees well with the value expected for early-type galaxies: assuming $M / L = 4$ (at the low end of the range for early type galaxies, and thus appropriate for this post-starburst example), the predicted velocity dispersion from a modern determination of the Faber-Jackson relation in the Coma cluster (Matkovic & Guzman 2007) is $\sigma = 230$ km s$^{-1}$. 

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**Figure 6.** Observed composite spectra (red, thick line) compared to models (overlaid, thin black line). From top to bottom: PSB galaxies with and without IR emission, of star-forming galaxies and dusty starbursts. Broad-band galaxy photometry, rather than the spectroscopic continuum, was used in the fitting procedure. The fits were to these broad band colors and the equivalent widths of the emission and absorption lines, not the shape of the lines. The high SFR fits are acceptable except for the infrared post-starburst spectrum (IR k+a), which has significantly broader Balmer absorption lines than the model. The bottom of the two templates for IR-detected k+a galaxies shows a poor fit to the width of the Balmer absorption lines. The top spectrum shows that we are able to reproduce the Balmer line profiles by smoothing the model fit to correspond to a velocity dispersion of 250 km s$^{-1}$, which is appropriate for elliptical galaxies of the mass of the average k+a in the composite.
Figure 7. Star formation rate as a function of SSP age for the best-fit models of PSB galaxies with IR emission (IR k+a), PSB galaxies without IR emission (k+a), star-forming galaxies [e(c)], and dusty starbursts [e(a)]. SFRs are in $M_\odot$ yr$^{-1}$, averaged over the number of galaxies of each spectral class. Age = 0 corresponds to the epoch of observation. Green dots indicate the value of E(B-V) for each stellar population, with the scale shown on the right.

The average galaxy stellar mass for this class is somewhat lower than for the Spitzer-detected post-starbursts, yielding $1.1 \times 10^{11} M_\odot$ regardless of the IR limits adopted, while the mass fraction formed during the last $6 \times 10^8$ yr varies significantly depending on whether no IR emission or IR upper limits are included in the fit, $\sim 20\%$ versus 9\%.

The PSB galaxies with and without a Spitzer detection have in common a history where a significant fraction, 10–30\% of the galaxy mass has formed in a recent burst with exceptionally high star formation rates. A lower limit for the SFR during the burst can be estimated from the average SFR during the last $6 \times 10^8$ yr, thus SFR $> 20–70 M_\odot$ yr$^{-1}$.

7.2. Emission-line spectra

The star formation history that best fits the e(c) “continuously star-forming galaxy” composite spectrum is markedly different from the two similar starburst histories described above. The average SFR per galaxy in this group is about 7.5 $M_\odot$ yr$^{-1}$ over the typical galaxy’s history, between 1.6 (0.6) $M_\odot$ yr$^{-1}$ (null IR flux or upper limit) during the last $6 \times 10^8$ yr and 2.1 (1.5) $M_\odot$ yr$^{-1}$ during the last 2 $\times 10^7$ yr before OE. Recent and ongoing SF levels are low, significantly lower than the all-time past average. It is important to stress that the variations of SFR over a single stellar population should not be considered significant, as the model cannot have such detailed time resolution. The overall SFR trends, as quantified in the broad age intervals presented in Table 2, are significant, but smaller intervals with higher or lower SFRs are not. For example, in the case of the e(c) galaxies, we note that the observed composite spectrum is noisier than in the post- or dusty- starburst composites, due both to the small number of objects (7) and their relative faintness. The full star formation history shown in Figure 7 for the e(c) shows many ups and downs, but these are not statistically significant. The overall star formation history—with these data—can best be interpreted as strong in the first few Gyr ($z \sim 2$) and steadily declining thereafter. Unlike the post-starbursts discussed above, and the dusty-starbursts discussed next, there are no important bursts for many Gyr before OE.

The stellar mass determined by the model for the average galaxy in the e(c) group is around $7 \times 10^{10} M_\odot$, lower than the either of the post-starburst types discussed above.

The average galaxy mass is even lower for the fit of the e(a) “dusty-starburst” spectrum: for the typical galaxy in this class $M = 2.5 \times 10^{10} M_\odot$. The model history of the dusty starbursts is consistent with an all-time average SFR per galaxy of 2.7 (2.8)

|      | IR-det. k+a | Undet. k+a | e(c)    | e(a)     |
|------|-------------|------------|---------|---------|
| Nobj | 6           | 12         | 8       | 19      |
| “all-time” | 16 $\pm$ 3 | 12 $\pm$ 2 | 7(7) $\pm$ 3 | 3(3) $\pm$ 0.8 |
| $6 \times 10^9$yr | 72 $\pm$ 7 | 30(17) $\pm$ 5(1) | 1(2) $\pm$ 2 | 6(7) $\pm$ 2 |
| $2 \times 10^7$yr | 9 $\pm$ 1  | 1.1 $\pm$ 0.1 | 1(2) $\pm$ 1 | 7(7) $\pm$ 3 |
| SFR(24 $\mu$m) | 12.1       | $\leq$3.0  | 1.5     | 7.7     |
| Mass | 1.5 $\pm$ 0.3 $\times 10^{11}$ | 1.1 $\pm$ 0.1 $\times 10^{11}$ | 7 $\pm$ 0.6 $\times 10^{10}$ | 2.5 $\pm$ 0.6 $\times 10^{10}$ |

**Notes.** Average SFR ($M_\odot$ yr$^{-1}$) per galaxy of each spectral class, as determined in the models. The SFR is averaged over the last 2 $\times 10^7$, 6 $\times 10^8$ and over the age of the Universe at $z = 0.4$—“all-time.” 9.2 $\times 10^9$ yr. The values in parentheses come from adopting the 24 $\mu$m upper limit as opposed to the null value, in case of nondetection. The SFR(24 $\mu$m) values, actual measurements, are to be compared to the 2 $\times 10^7$ yr SFR from the model, as explained in the text. The last row contains the average galaxy stellar mass in solar masses.
(null IR or upper limit), while the recent and ongoing SFRs are 6.4 (6.6) during the last $6 \times 10^8$ yr and 6.9 (7.3) during the last $2 \times 10^7$ yr. The recent star formation in these galaxies is therefore more than twice the all-time average. The rise in SFR compared to the $\sim 10^9$ years immediately preceding the burst might actually be more than a factor-of-two, because most massive galaxies show histories of monotonically declining SFR over time, in other words, using the “all-time” average is likely to be an upper limit for the period immediately preceding the burst. The modeling cannot, without very high S/N spectra, resolve this difference, but a more accurate assessment of the rise in SFR compared to the time immediately preceding the burst would be important in understanding the actual physical conditions and mechanisms that might be responsible.

In summary, the e(a) galaxies have had starbursts like the k+a types, but these starbursts—substantially hidden by dust—are continuing at the OE.

Table 2 contains a summary of the model results for each of the different spectral classes, including the SFR per galaxy averaged over the last $2 \times 10^7$, $6 \times 10^7$ and over the age of the universe at $z = 0.4$ (“all-time”), $t = 9.2 \times 10^9$ yr. Also listed is the number of galaxy spectra which contributed to each composite spectrum. The classification into spectral classes has clearly identified galaxies with markedly different stellar histories. The k+a galaxies are once more confirmed to be PSB galaxies, with or without (depending on IR detection) residual star formation activity. Among the emission-line galaxies, the star formation activity has declined with time in e(c) galaxies without a detectable burst, while in e(a) galaxies there is a mild-to-moderate burst of star formation at the OE.

The models are constrained to reproduce the FIR luminosity inferred from the mid-IR luminosity, not the SFR as indicated from the 24 $\mu$m measurements (Section 4.3). Nevertheless, we find good agreement between what the modeling returns for the SFR over the time bin $2 \times 10^7$ yr and our “direct” determination of the SFR from the mid-IR. The agreement is not expected to be exact because (1) the FIR (from mid-IR) flux is one of many constraints in the models, and (2) the two paths incorporate different assumptions about the initial mass function and the timescales for the relevant calculations.

We summarize this section by noting that the star formation histories derived with the spectral modeling of star formation are consistent with the simple picture presented in Section 5 where we compared 24 $\mu$m and [O II] fluxes to distinguish the histories of galaxies of the different spectral classes. The results of this small, first study using Spitzer-MIPS data are consistent with the idea that e(a) and e(b) galaxies are active starbursts, k+a galaxies are the post-starburst phase of those galaxies, and e(c) galaxies are those that have not experienced any starbursts in the past few billion years. The numbers of cases and spectra are sufficiently small that we must consider this a preliminary step toward confirming the Poggianti et al. (1999) interpretation of galaxy spectra in intermediate-redshift clusters. For example, the e(a) galaxies studied here have a mass 2–3 times smaller than the two types of post-starbursts. This could easily be the result of the small sample sizes, but if it were to be confirmed with the much larger study we have begun, this would provide a puzzling distinction that would not fit with the simple model.

Cycle GO-4 observations of 27.5 hrs (PID 40387, P.I.: A. Dressler) have been awarded to extend the coverage of Abell 851, and to observe two additional clusters at similar redshift, for which large spectroscopic samples of field and cluster galaxies have been obtained. These data should allow further investigation of obscured star formation in this cluster and its relevance to other intermediate-redshift galaxy populations.

8. CONCLUSIONS

Our study of optical spectroscopy and Spitzer-MIPS observations of a spectroscopic sample of cluster members of A851 at $z = 0.42$ has yielded the following results. (1) Detection with MIPS at 24 $\mu$m is a strong function of spectral type: almost all passive galaxies are undetected, and most normal star-forming galaxies (type e(c), weak H$\delta$ absorption) are also undetected. However, some PSB galaxies (strong H$\delta$) and most e(a) galaxies (strong H$\alpha$ and [O II] emission) are detected. The nondetection of e(c) galaxies as compared to the detection of most e(a) galaxies occurs across the full range of luminosity sampled—in fact, the e(c)’s are systematically more massive in this sample—so this difference in detection is not a selection effect. (2) For the e(a) galaxies, the SFR derived from 24 $\mu$m is typically several times that inferred from [O II], indicating a substantial amount of dust obscuration of ongoing star formation in these systems. Ongoing star formation is seen in some galaxies classified as post-starburst, for which SFR(24 $\mu$m)/SFR([O II]) is likely to be as much as a factor of 10, but this represents a significant decline from the burst that came before. (3) The high rates of star formation in e(a) galaxies—factors of 2–3 above the past average for these systems—qualifies them as moderate starbursts capable of accounting for the post-starbursts seen in A851, although for the specific, small samples we have here, there is a factor of 2–3 lower mass associated with the e(a) compared to the k+a galaxies. (4) A small sample of present-day star-forming galaxies shows that these typically have SFR(IR)/SFR(optical) $\sim 1$. We suggest that these galaxies are like the e(c) galaxies in A851, which would be consistent with these objects having 24 $\mu$m flux below the detection limit of these observations.

The assembly of these observations supports the model in which the e(a) galaxies and even some PSB galaxies are actually dust-obscured starbursts, with a factor of $\sim 4$ of the star formation hidden. As we will show in a forthcoming paper, the significant fraction of e(a) spectra among field galaxies at intermediate-redshift suggests that starbursts are also relatively common among field galaxies at intermediate-redshift. The rarity of such objects in the present-epoch universe indicates that star formation in ordinary spirals was more bursty—more variable—as recently as 4 Gyr ago. The extent and magnitude of this phenomenon will become increasingly clear as further Spitzer–MIPS observations become available for intermediate-redshift clusters and the field.

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