Reversal of Fortune: Confirmation of an Increasing Star Formation-Density Relation in a Cluster at $z = 1.62$

Tran, K V H; Papovich, C; Saintonge, A; et al

Abstract: We measure the rest-frame colors (dust-corrected), infrared luminosities, star formation rates, and stellar masses of 92 galaxies in a Spitzer-selected cluster at $z = 1.62$. By fitting spectral energy distributions (SEDs) to 10-band photometry ($0.4 \text{ m} < \text{obs} < 8 \text{ m}$) and measuring 24 m fluxes for the 12 spectroscopically confirmed and 80 photometrically selected members, we discover an exceptionally high level of star formation in the cluster core of 1700 M sun yr$^{-1}$ Mpc$^{-2}$. The cluster galaxies define a strong blue sequence in $(U-V)$ color and span a range in color. We identify 17 members with $L_{\text{IR}}>10^{11}$ L sun, and these IR luminous members follow the same trend of increasing star formation with stellar mass that is observed in the field at $z < 2$. Using rates derived from both the 24 m imaging and SED fitting, we find that the relative fraction of star-forming members triples from the lowest to highest galaxy density regions; e.g., the IR luminous fraction increases from 8% at $\Sigma < 10$ gal Mpc$^{-2}$ to 25% at $\Sigma > 100$ gal Mpc$^{-2}$. The observed increase is a reversal of the well-documented trend at $z < 1$ and signals that we have reached the epoch when massive cluster galaxies are still forming a substantial fraction of their stars. This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion laboratory, California Institute of Technology, under NASA contract 1407. This Letter also includes data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile. This work is based in part on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

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REVERSAL OF FORTUNE: CONFIRMATION OF AN INCREASING STAR FORMATION-DENSITY RELATION IN A CLUSTER AT Z = 1.62

Kim-Vy H. Tran1,2,3, Casey Papovich4, Amélie Saintongé5, Mark Brodwin6, James S. Dunlop6, Duncan Farrah7, Keely D. Finkelstein2, Steven L. Finkelstein2, Jennifer Lotz2, Ross J. McLure5, Ivelina Momcheva5, & Christopher N. A. Willmer10

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ABSTRACT

We measure the rest-frame colors (dust-corrected), infrared luminosities, star formation rates, and stellar masses of 92 galaxies in a Spitzer-selected cluster at z = 1.62. By fitting spectral energy distributions (SEDs) to 10-band photometry (0.4μm < λabs < 8μm) and measuring 24μm fluxes for the 12 spectroscopically confirmed and 80 photometrically selected members, we discover an exceptionally high level of star formation in the cluster core of ∼ 1700 M⊙ yr⁻¹ Mpc⁻². The cluster galaxies define a strong blue sequence in (U−V) color and span a range in color. We identify 17 members with LIR > 10¹¹ L⊙, and these IR luminous members follow the same trend of increasing star formation with stellar mass that is observed in the field at z ~ 2. Using rates derived from both the 24μm imaging and SED fitting, we find that the relative fraction of star-forming members triples from the lowest to highest galaxy density regions, e.g. the IR luminous fraction increases from ∼ 8% at Σ ∼ 10 gal Mpc⁻² to ∼ 25% at Σ ≥ 100 gal Mpc⁻². The observed increase is a reversal of the well-documented trend at z < 1 and signals that we have reached the epoch when massive cluster galaxies are still forming a substantial fraction of their stars.

Subject headings: galaxies: evolution – galaxies: starburst – galaxies: clusters: individual (ClG J0218.3-0510) – infrared: galaxies

1. INTRODUCTION

A well-established observational hallmark of how galaxies evolve as a function of environment is the star formation-density relation. A plethora of studies utilizing multi-wavelength tracers of activity have shown that star formation universally decreases with increasing galaxy density as a function of environment is quenched as a function of galaxy mass and environment provides strong constraints on galaxy models (e.g. Kauffmann et al. 1993, Hopkins et al. 2008). Indeed, galaxy mass or the larger scale environment the primary driver of evolution?

Observations of field galaxies at z ~ 1 indicate that the star formation-density relation turns over at this epoch such that there is an enhancement of activity in the highest density regions of the field (Elbaz et al. 2007, Cooper et al. 2008). Studies also find an excess of dust-obscured star formation in group environments at z < 1 (Koyama et al. 2008, Tran et al. 2009, Gallazzi et al. 2009), and very recent results suggest that star formation may be enhanced in the significantly richer regions of high density clusters (Elbaz et al. 2007, Cooper et al. 2008). As cluster surveys push to higher redshifts (z > 1) and thus closer to the epoch when massive galaxies are forming their stars, variations in age will become evident in, e.g. a larger scatter in color, and robust star formation rates should reveal increasing levels of activity even in the cluster cores.

We report here the first confirmation of increasing star formation activity with increasing galaxy density observed in cluster CIG J0218.3–0510, a Spitzer-selected galaxy cluster at z = 1.62 (Papovich et al. 2010, hereafter Pap10). We use cosmological parameters Ω_m = 0.3, Λ = 0.7, and H = 70 km s⁻¹ Mpc⁻¹ throughout the paper; at z = 1.62, this corresponds to an angular scale 0.5 Mpc arcmin⁻¹. All magnitudes are in the AB system.

2. MULTI-WAVELENGTH DATA

CIG J0218.3–0510 has a wealth of multi-wavelength imaging data that includes BRIz imaging from the Subaru-XMM Deep Survey (Furusawa et al. 2008) and JK imaging from the UKIRT IR Deep Sky Survey (UKIDSS, Lawrence et al. [2010])...
for these data, we utilized the K–selected catalog from Williams et al. (2009). The cluster field also has deep Spitzer imaging available in the four IRAC bands (3.6–8.0 μm) and MIPS 24 μm as part of the Spitzer public legacy survey of the UKIDSS Ultra Deep Survey (SpUDS, PI: J. Dunlop). We matched the K–band selected catalog to the IRAC data following Papovich et al. (2006).

CIG J0218.3-05101 was originally detected as a strong overdensity of galaxies at 1.5 < z_{pho} < 1.7 with a mean surface density > 20σ higher than that of galaxies in the same redshift range in the UKIDSS Ultra-Deep Survey (Lawrence et al. 2007). Follow-up spectroscopy confirmed 10 members that define a narrow redshift peak at 1.622 ≤ z ≤ 1.634 with additional members at z = 1.609 and z = 1.649 (Pap10; Tanaka et al. 2010). In our analysis, we include 80 more members that are selected from photometric redshifts determined with EAZY (Brammer et al. 2008); we use the limit for the integrated redshift probability defined by the spectroscopically confirmed members (P_{z} > 0.3; see Pap10 for a detailed description of the photometric selection).

Analysis of XMM-Newton data in this field also reveals a weak detection consistent with extended emission from the cluster. The cluster mass estimated from its X-ray luminosity is ξ ~ 1 × 10^{14} M_☉ and consistent with its estimated dynamical mass of 4 × 10^{14} M_☉. To define the cluster center, we select the massive (spectroscopically confirmed) member located at the peak of the X-ray emission: its J2000 coordinates are (2:18:21.07, -5:10:32.84), and all of the cluster galaxies lie within R_{proj} ~ 1 Mpc of this member.

2.1. Spectral Energy Distributions

We fit the 10–band galaxy photometry (0.4 μm < λ_{obs} < 8 μm) with the 2007 version of the Bruzual & Charlot (2003) stellar population synthesis models using a Chabrier initial mass function (for more details, see Papovich et al. 2006). We find that models with Solar metallicity best reproduce the rest-frame colors and scatter of the cluster red sequence galaxies (Pap10), and we allow the models to range in age from 10^6 to 2 × 10^10 yr; we also include dust attenuation using the Calzetti et al. (2000) law with color excess values ranging from E(B–V) = 0.0–0.7. We allow for a range of star formation histories parameterized as a decaying exponential with an e–folding time τ, where at any age t the star formation rate is Ψ(t) = ψ_0 exp(–t/τ) and τ ranges from 1 Myr to 100 Gyr (corresponding approximately to instantaneous bursts to constant star formation, respectively). In the model fitting, we add a σ/f_r = 5% error in quadrature to the photometric uncertainties on each band to account for mismatches in the multi-band photometry, and for the fact that the models do not continuously sample the model parameter space. Our sample of 92 cluster members has an average best-fit age of ~ 500 Myr and an average best-fit τ of ~ 500 Myr; 35 members have SED-derived star formation rates >5 M_☉ yr^{-1}.

2.2. MIPS 24 μm Fluxes

The cluster field was imaged with Spitzer MIPS as part of the legacy UKIDSS Ultra Deep Survey (SpUDS; PI: J. Dunlop). We extracted sources from the public SpUDS 24 μm map using StarFinder (Diolaiti et al. 2000), an IDL-based PSF-fitting code designed for crowded fields. The 24 μm image has 1.245'' pixel^{-1}, and we derived a model PSF and aperture corrections from the brightest isolated sources from the SpUDS image. The catalog includes all sources detected with S/N > 5; this corresponds to a flux of ~ 40 μJy. Using simulated sources based on the PSF and injected into the map, we determine that the catalog is 80% complete at this flux level.

The measured 24 μm fluxes are converted into total infrared luminosities (L_{IR}) using the Chary & Elbaz (2001) templates. Recent Herschel studies indicate that while this technique is very accurate at z < 1.5, extrapolations from monochromatic 24 μm fluxes overestimate the true L_{IR} by factors of 2–7 at z > 1.5 (e.g., Nordon et al. 2010). Finally, star formation rates are calculated from L_{IR} using the prescription of Kennicutt (1998), adjusted to the Chabrier IMF.

3. STELLAR MASSES, STAR FORMATION RATES, AND ENVIRONMENT

By fitting SEDs to the 10-band photometry (0.4 μm < λ_{obs} < 8 μm), we are able to measure accurate rest-frame colors (AB system) and stellar masses as well as correct for dust extinction. Figure 1 shows the measured and dust-corrected rest-frame (U–V) color versus stellar mass for the 92 cluster

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11 http://ssc.spitzer.caltech.edu/spitzermission/observingprograms/legacy/spuds/
12 At z = 1.62, this corresponds to a rest-frame wavelength range of 0.15 μm < λ_{rest} < 3.0 μm.
galaxies within $R_{\text{proj}} \sim 1 \text{ Mpc}$ of the BCG. As demonstrated by, e.g. Wyder et al. (2007), the galaxies begin to separate into the well-known bimodal distribution only when the colors are corrected for extinction.

The ClG J0218.3-0510 members differ from their counterparts in clusters at $z \lesssim 1.2$ (e.g. Holden et al. 2006; Rettura et al. 2010) in that they have a color-stellar mass distribution that is surprisingly similar to that observed in the field at $z \sim 2$ (Brammer et al. 2009): the ClG J0218.3-0510 members define a strong blue sequence and span a range in (dust-corrected) color (Fig. 2, bottom panel). While these members populate a red sequence in the $(z-J)$ color-magnitude diagram (Pap10), the correlation between rest-frame $(U-V)$ color and stellar mass is visibly weaker. However, the most massive galaxies ($M_* \sim 10^{11} M_\odot$) are still the reddest, i.e. they have the oldest stellar populations.

Seventeen of the members are detected at 24$\mu$m (Fig. 1), and the most IR luminous members include some of the most massive cluster galaxies (Fig. 2). Figure 2 shows that these IR luminous members follow the same trend of increasing star formation with stellar mass that is observed in the field at $z \sim 2$ by Daddi et al. (2007). Note that because we can only detect members that are IR-bright ($L_{\text{IR}} \gtrsim 3 \times 10^{11} L_\odot$), we are sensitive only to the upper envelope of the trend observed at $z \sim 2$.

Three of the ClG J0218.3-0510 members are Ultra-Luminous Infrared Galaxies (ULIRGs; $L_{\text{IR}} \gtrsim 10^{12} L_\odot$; see Fig. 2) and the remaining 14 are LIRGs ($10^{11} \lesssim L_{\text{IR}} < 10^{12} L_\odot$). In stark contrast, the > 2000 galaxies in clusters at $z < 1$ studied with wide-field ($R_{\text{proj}} \gtrsim 1 \text{ Mpc}$) mid-IR imaging (e.g. Geach et al. 2008; Saintonge et al. 2008; Smith et al. 2010), only one is a ULIRG and it lies outside the core of the Bullet Cluster, a well-known cluster-cluster merger at $z = 0.297$ (Chung et al. 2010). The higher fraction of IR luminous galaxies at $z = 1.62$ is likely to be driven by the overall evolution of the IR luminosity function in clusters (e.g. Bai et al. 2009), however, more deep IR imaging of clusters at $z > 1$ is needed to confirm this trend.

In our analysis, we assume that the 24$\mu$m sources are dominated by star formation and do not harbor active galactic nuclei (AGN). From the SED fits, we find that two of the 24$\mu$m detected members with star formation rates $\gtrsim 40 M_\odot$ yr$^{-1}$ (open stars) and members with SED-derived rates $>5 M_\odot$ yr$^{-1}$ (bottom; open triangles). The open circles in both panels show the 24$\mu$m detected members in the massive galaxy cluster CL 1358+62 at $z = 0.33$ (Tran et al. 2009) and represents the well-established trend documented at $z < 1$; these circles are offset slightly in log $\Sigma$ for clarity. Errorbars are determined from bootstrapping the data in each bin 1000 times.

The fraction of star-forming members is highest in the regions with the highest galaxy density, a reversal of the trend at $z < 1$. At $z = 1.62$, we have reached the epoch when massive cluster galaxies are still forming a significant number of new stars.
without these two members confirms that our overall results do not change.

In the cluster core ($R_{\text{proj}} < 0.5$ Mpc), the star formation rate density from the 24$\mu$m photometry alone is $\sim 1700 M_\odot$ yr$^{-1}$ Mpc$^{-2}$; we stress that this is likely a lower limit given the 24$\mu$m imaging cannot detect any members with SFR$_{IR} \lesssim 40 M_\odot$ yr$^{-1}$, i.e. with star formation rates typical for IR-detected galaxies in clusters at $z < 1$. Only one other galaxy cluster at $z = 1.46$ has a comparably high star formation rate in its core (Hayashi et al. 2010; Hilton et al. 2010). In comparison, studies of IR-detected galaxies in clusters at $z < 1$ find that star-forming members are strongly segregated at $R_{\text{proj}} > 0.5$ Mpc (Geach et al. 2006; Saintonge et al. 2008; Kovaya et al. 2008).

Given the high star formation rate in its core, does CIG J0218.3-0510 follow the well-established trend at $z < 1$ of decreasing star-formation with increasing galaxy density (e.g. Hashimoto et al. 1998; Ellingson et al. 2001; Gómez et al. 2003)? Figure 3 compares the relative fraction of star-forming members to passive members as a function of local galaxy density ($\Sigma$), which is defined by distance to the 10th nearest neighbor (Dressler 1980). We use star-formation rates derived from the 24$\mu$m imaging as well as from the SED fitting because the two independent star formation tracers complement each other and provide an important check of our results: The 24$\mu$m imaging is a robust measure of the dust-obscured star formation but only detects the most active members (\(\gtrsim 40 M_\odot\) yr$^{-1}$) while the SED fitting is sensitive to lower levels of unobserved activity (\(\gtrsim 5 M_\odot\) yr$^{-1}$).

Both star formation tracers confirm that the relative fraction of active members is highest in the regions of highest galaxy density (Fig. 4), i.e. exactly opposite to that observed in clusters at $z < 1$. A Spearman rank test supports with $> 97\%$ confidence (\(> 2\sigma\) significance) that the relative fraction of IR luminous members increases with increasing galaxy density from \(\sim 8\%\) at \(\Sigma \sim 10\) gal Mpc$^{-2}$ to \(\sim 25\%\) at \(\Sigma \gtrsim 100\) gal Mpc$^{-2}$. We stress that excluding the two candidate AGN does not change the trend, and the robustness of this result is underscored by the fact that we see the same trend using the SED-derived rates. While studies of galaxies in the field at $z \sim 1$ (\(\Sigma < 10\) gal Mpc$^{-2}$) find that the star formation-density relation is beginning to turn over at this epoch (Elbaz et al. 2007; Cooper et al. 2008), this is the first confirmation of such a reversal in the significantly higher density environment of galaxy clusters.

The measured IR luminosities correspond to specific star formation rates (star formation rate divided by stellar mass; SSFR) per Gyr of \(\sim 1\) to \(20\); these active members can more than double their stellar masses in the next Gyr (by $z \sim 1.2$). However, to reproduce the relatively homogeneous stellar ages measured in massive cluster galaxies at $z < 1$ (e.g. Blakeslee et al. 2006; Tran et al. 2007; Mei et al. 2009), these IR luminous members cannot maintain such a high SSFR for even a Gyr. The current star formation must be quenched rapidly and any later bursts of activity cannot add a substantial amount of new stars, at least not in the massive members (log$(M_\ast)$ \([M_\odot] > 10.6\)) that must populate a well-defined red sequence by $z \sim 0.8$.

4. CONCLUSIONS

We measure the rest-frame colors (dust-corrected), IR luminosities, star formation rates, and stellar masses of galaxies in CIG J0218.3-0510, a Spitzer-selected cluster at $z = 1.62$, by fitting spectral energy distributions to photometry in 10 bands ($0.4 \mu m < \lambda_{\text{obs}} < 8 \mu m$) and with deep 24$\mu$m imaging. The cluster sample (Pap10; Tanaka et al. 2010) is composed of 12 spectroscopically confirmed members and 80 members selected from photometric redshifts measured using EAZY (Brammer et al. 2008); all members are within $R_{\text{proj}} \lesssim 1$ Mpc of the massive cluster galaxy located at the peak of the X-ray emission.

The 92 cluster members have a color-stellar mass distribution that is surprisingly similar to that observed in field galaxies at $z \sim 2$. When corrected for dust, the cluster members define a strong blue sequence and span a range in color, indicating a substantial amount of recent and ongoing star formation in the cluster core. This dramatic level of activity is underscored by the 17 members detected at 24$\mu$m. In the cluster core ($R_{\text{proj}} < 0.5$ Mpc), the star formation rate density from the IR luminous members alone is $\sim 1700 M_\odot$ yr$^{-1}$ Mpc$^{-2}$; the true value is likely to be higher given that we only include members with SFR$_{IR} \gtrsim 40 M_\odot$ yr$^{-1}$. These IR luminous members also follow the same trend of increasing star formation with stellar mass that is observed in the field at $z \sim 2$.

We discover the striking result that the relative fraction of star-forming galaxies increases with increasing local galaxy density in CIG J0218.3-0510, a reversal of the well-established trend at lower redshifts and in line with recent work at $z \sim 1.46$ that suggests enhanced star formation in cluster cores. Measurements using star formation rates derived from the 24$\mu$m imaging and from the SED fitting provide independent confirmation that the relative fraction of star-forming galaxies triples from the lowest to highest density regions. By pushing into the redshift desert ($z \gtrsim 1.6$), we are able to reach the epoch when massive cluster galaxies are still forming a significant number of their stars.

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