HIERARCHICAL FORMATION IN ACTION: CHARACTERIZING ACCELERATED GALAXY EVOLUTION IN COMPACT GROUPS USING WHOLE-SKY WISE DATA

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Received 2015 August 9; accepted 2016 March 3; published 2016 April 20

ABSTRACT

Compact groups provide an environment to study the growth of galaxies amid multiple prolonged interactions. With their dense galaxy concentrations and relatively low velocity dispersions, compact groups mimic the conditions of hierarchical galaxy assembly. Compact group galaxies are known to show a bimodality in *Spitzer* IRAC infrared color space: galaxies are preferentially either quiescent with low specific star formation rates (SSFRs) or prolifically forming stars—galaxies with moderate levels of specific star formation are rare. Previous *Spitzer* IRAC studies identifying this “canyon” have been limited by small number statistics. We utilize whole-sky *Wide-field Infrared Survey Explorer* (*WISE*) data to study 163 compact groups, thereby tripling our previous sample and including more galaxies with intermediate mid-IR colors indicative of moderate SSFRs. We define a distinct *WISE* mid-IR color space $\left(\log\left[\frac{f_{12}}{f_{4.6}}\right]\right)$ versus $\left(\log\left[\frac{f_{22}}{f_{3.4}}\right]\right)$ that we use to identify canyon galaxies from the larger sample. We confirm that compact group galaxies show a bimodal distribution in the mid-infrared and identify 37 canyon galaxies with reliable photometry and intermediate mid-IR colors. Morphologically, we find that the canyon harbors a large population of both Sa–Sbc and E/S0 type galaxies, and that they fall on the optical red sequence rather than the green valley. Finally, we provide a catalog of *WISE* photometry for 567 of 652 galaxies selected from the sample of 163 compact groups.

Key words: galaxies: evolution – galaxies: groups: general – galaxies: interactions

Supporting material: machine-readable table

1. INTRODUCTION

With their high number densities, low velocity dispersions, and frequent reservoirs of intragroup diffuse gas (Hickson et al. 1992), compact groups are dense associations of three or more bright galaxies that routinely undergo prolonged gravitational interactions (Hickson et al. 1992). Due to these properties, they bear a strong resemblance to conditions in the earlier universe, making them an ideal laboratory for studying physical processes such as the formation of central supermassive black holes, galaxy clusters, super star clusters, and dwarf galaxies experiencing multiple interactions (Konstantopoulos et al. 2013; Tzanavaris et al. 2014). Compact groups also play a critical role in understanding galaxy evolution, as their frequent gravitational interactions affect the gas processing and specific star formation rates (SSFRs; star formation rate per stellar mass) of member galaxies. They also tend to be more difficult to characterize than either galaxy clusters or merging pairs: unlike virialized galaxy clusters with thousands of members, compact groups may be more sensitive to the initial configuration of the handful of group members, and unlike galaxy pair mergers, initial conditions in compact

groups are more difficult to constrain with models due to a large number of free parameters.

In order to assess the impact of the compact group environment on star formation and galaxy evolution, Johnson et al. (2007) studied the mid-infrared colors of these galaxies and discovered an underdensity between compact group galaxies that are actively star-forming and those that are relatively quiescent. The underdensity in color space suggests a rapid transformation of galaxy properties, in the sense that this dearth in *Spitzer* IRAC color space $\left(\log\left[\frac{f_{8.0}}{f_{4.5}}\right]\right)$ versus $\left(\log\left[\frac{f_{5.8}}{f_{3.6}}\right]\right)$ is a transition region between spirals and bulge-dominated galaxies (Walker et al. 2010). This transition region, or IRAC “canyon,” is occupied by relatively few galaxies with moderate SSFRs and not seen in comparison samples of field galaxies, interacting pairs, or the center of the Coma Cluster (Walker et al. 2010, 2012). The Coma infall region is the only comparison sample that shows a similar distribution to compact group galaxies in IRAC color space (Walker et al. 2012). This is consistent with the idea that the infall region best mimics the properties of the compact group environment, as they both have high galaxy densities and reservoirs of cold gas. Finally, in addition to showing a bimodality in mid-IR color space,

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Tzanavaris et al. (2010) also find a significant gap between low ($\leq 4.3 \times 10^{-12} \text{ yr}^{-1}$) and high ($\geq 1.6 \times 10^{-11} \text{ yr}^{-1}$) SSFR systems in the compact group environment. The recent work of L. Lenkic et al. (2016, in preparation) further supports this SSFR bimodality. The lack of compact group galaxies with moderate levels of specific star formation, in contrast to other environments, implies that compact group galaxies experience accelerated evolution. Star formation enhancement due to gravitational interactions (including mergers) of galaxies in this dense environment likely also plays a role in this observed bimodality.

To further investigate the nature of compact group galaxies, Cluver et al. (2013) used the *Spitzer* Infrared Spectrograph (IRS) to study the polycyclic aromatic hydrocarbon (PAH) and H_2 lines in the systems. The first compact group studied in detail in this way was Stephan’s Quintet (Appleton et al. 2006; Cluver et al. 2010), where enhanced warm H_2 emission was seen in quantities that could not be explained by photoionization from star-forming regions alone. This emission was associated with the large bow shock seen between the intruder (NGC 7319) and the interacting pair (NGC 7318a and 7318b). Cluver et al. (2013) followed up this effort, investigating the mid-IR spectral properties of 74 galaxies in 23 Hickson Compact Groups (HCGs), including 17 galaxies within the original IR gap of Johnson et al. (2007). These results show that the galaxies that are in the IR gap are the most likely to show enhanced warm H_2 from *Spitzer*, and thus are considered galaxies most likely to have shock-enhanced interstellar media (ISMs), hinting that shocks in these systems might be a significant contributor to canyon galaxies’ rapid evolution.

All previous IR-based studies—using data from the *Spitzer Space Telescope*—are limited by their small sample sizes. Johnson et al. (2007) studied only 12 compact groups (45 galaxies), while Walker et al. (2012) only studied 49 compact groups (174 galaxies). The largest sample (Walker et al. 2012) yielded only five galaxies located in the mid-infrared canyon region, a minuscule number when one seeks to understand the properties of these unique galaxies and their evolution. The small sample sizes of previous studies are due to both limited sky coverage and the narrow imaging bands of *Spitzer*, which forces a redshift cut as the PAH features shift out of the $8 \mu\text{m}$ band at $z = 0.035$. In contrast, the *Wide-field Infrared Survey Explorer* (WISE) telescope has whole-sky coverage and bands wide enough that the PAH features do not shift out of the $12 \mu\text{m}$ band until $z = 0.52$. Using WISE data, we perform analyses similar to those of Johnson et al. (2007) and Walker et al. (2012). We expand the sample selection to a total of 163 compact groups (652 member galaxies), thereby drawing from all 49 groups from Walker et al. (2012), plus an additional 114 groups, increasing the number of compact groups with mid-IR analyses by a factor of three. In doing so, we are able to identify additional galaxies in the mid-infrared canyon region, producing a sizable sample of moderate SSFR galaxies that will enable a more comprehensive analysis of the processes that influence galaxy evolution in this environment.

2. DATA

2.1. Sample

For this study, we draw our sample from groups in the HCG catalog (Hickson 1982) and the Redshift Survey Compact

Group catalog (RSCG; Barton et al. 1996). Since our sample is culled from two different catalogs, it is necessary to consider their differing selection criteria. The original 100 HCGs were identified through a systematic visual search of the Palomar Observatory Sky Survey prints. In the original sample, each HCG had to contain at least four galaxies (within three magnitudes of the brightest galaxy) and had to satisfy isolation and compactness criteria—requirements that excluded the addition of galaxy clusters in the catalog. Follow-up radial velocity data indicated that several groups had only three members within 1000 km s^{-1} of the median group velocity, but these groups were not rejected (Hickson et al. 1992). Seven other groups (HCGs 9, 11, 18, 36, 41, 77, 78) were shown to have less than three accordant members, and these groups are excluded from our analysis (Hickson et al. 1992). Following the convention from Hickson et al. (1992), we also exclude discordant galaxies that by projection appear to be members of accordant groups.

In contrast to the HCGs, the 89 RSCGs were chosen from a complete, magnitude-limited redshift survey, using a friends-of-friends algorithm, with parameters chosen to identify compact groups similar to the HCGs (Barton et al. 1996). “Neighbors” were identified based on projected separation ($\Delta d < 50 \text{ kpc}$) and median radial velocity difference ($\Delta v < 1000 \text{ km s}^{-1}$). The radial velocity criterion is concordant with Hickson’s procedure of rejecting group members with a median line-of-sight velocity difference $> 1000 \text{ km s}^{-1}$ (Hickson et al. 1992). Unlike Hickson, Barton et al. (1996) did not take galaxy magnitudes into account, nor did they implement Hickson’s isolation criterion. As a result, some RSCGs are embedded in clusters, with the most extreme examples being RSCGs 67 and 68 (embedded in the Coma Cluster), RSCG 21 (embedded in the Perseus Cluster), and RSCG 11 (embedded in the core of Abell cluster 194). It is important to recognize that the cluster environment acts as a confounding variable in our analysis of the compact group environment, so we have excluded the most extreme examples—RSCGs 11, 21, 67, and 68—from our analysis. Several other RSCGs are located on the edge of clusters, including RSCG 12 on the outskirts of the Zwicky cluster (Barton et al. 1998), or RSCG 65 on the outskirts of the Virgo cluster (Barton et al. 1996). As the cluster outskirts environment is expected to be less of an influence than the cluster core environment (being the only other comparison sample from Walker et al. [2010] to exhibit a gap), we include these groups in our analysis. Finally, though the HCG and RSCG catalogs had different selection criteria, there are 15 RSCGs that are either HCGs or part of HCGs. In these instances, we only use the HCG group to avoid double-counting. Excluding all discordant HCGs (seven groups) and RSCGs embedded near the core of clusters (four groups), our final tally of distinct compact groups is 163 (93 HCGs and 70 RSCGs), totaling 652 constituent galaxies.

2.2. WISE Photometry

The original ALLWISE atlas images are intentionally blurred, with their point-spread function (PSF) profiles having FWHM values that are $\sqrt{2}$ times larger than the single-exposure values. As such, we utilize new ALLWISE coadds¹² from Lang (2014), which preserve the native resolution of the raw frames ($\approx 6''.1$, $6''.4$, $6''.5$, and $12''.0$ for bands $W1$, $W2$,

¹² <http://unwise.me/>

W3, and W4). We convert to janskys using $f_0 \times 10^{-0.4\text{MAGZP}}$, taken from Section 4.3 in the explanatory supplement for the ALLWISE image atlas. We adopt the same zero magnitude flux densities ($f_0 = 306.682, 170.663, 29.0448, \text{ and } 8.2839$ for W1, W2, W3, and W4) implemented in the conversion of ALLWISE source catalog raw fluxes to magnitudes, which assumes an $f_\nu \propto \nu^{-2}$ power-law spectrum. The zero-point value MAGZP equals 22.5 for all four bands, as Lang (2014) scales the reprocessed ALLWISE atlas images to this zero point. To ensure a common pixel scale and resolution, we convolve the W1 (3.4 μm), W2 (4.6 μm), and W3 (12 μm) images to the W3 PSF, using the WISE “frame” kernels from Aniano et al. (2011). We avoid convolving to the W4 (22 μm) PSF, as this band has low sensitivity and will only add noise for a majority of the galaxies. Instead, we derive an independent aperture for galaxies with high ratio (S/N) in W4 and pull the rest of the photometry from the ALLWISE source catalog for unresolved or low-S/N systems.

We perform photometry on the convolved W1, W2, and W3 images and select W4 images using SURPHOT, a multi-wavelength photometry code that measures flux densities within a single aperture across multiple wavebands (Reines et al. 2008). We use SURPHOT to detect a contour level (1σ – 3σ above the background) in a specified region of a reference image—an averaged, weighted (λ^{-1}) image of the W1, W2, and W3 bands (hereafter referred to as W123). As the W123 reference image is weighted by λ^{-1} , W1 drives the aperture, followed by W2 and W3. Once an aperture is determined using the reference image, SURPHOT assigns this reference aperture identically to the first three WISE bands. Three sets of background annuli are also applied by expanding the aperture in W123 by two specified factors (2.0 – $2.5\times$, 2.0 – $3.0\times$, 2.5 – $3.0\times$), which are then applied to the W1, W2, and W3 bands. For each annulus (2.0 – $2.5\times$, 2.0 – $3.0\times$, 2.5 – $3.0\times$), the background flux is calculated using both the mode and the resistant mean, which reduces the effect of neighboring galaxies contaminating the background annulus. These local background fluxes are then subtracted from the source flux. Uncertainties are calculated for all SURPHOT fluxes by determining the standard deviation in the set of fluxes due to differences in the background. As the background flux is calculated in six ways (mode and the resistant mean for the three types of background annuli), we determine the standard deviation in the set of six background-subtracted source fluxes.

Thus, we divide the photometry into three groups, based on their resolution and S/N in W1 through W4:

1. For galaxies resolved in W1, W2, W3, and W4, we perform photometry on W1, W2, and W3 with SURPHOT, applying a matched aperture derived from W123 to each of the first three convolved images. We then use SURPHOT to define an independent aperture using only the W4 image. To determine whether a source is resolved in W4, we use the reduced χ^2 of the W4 profile-fit photometry measurement (“w4rchi2”) from the ALLWISE source catalog. This parameter indicates the goodness of fit between the source and the PSF, with resolved and extended galaxies exhibiting larger χ^2 . We flag any galaxy with $\text{w4rchi2} > 2$ as a resolved and extended source. Of the 652 galaxies in our sample, 59 galaxies are individually resolved in the W123 reference image and also have $\text{w4rchi2} \geq 2$, so SURPHOT is used to calculate fluxes in all four bands.

2. For galaxies resolved in W1, W2, and W3, but with a $\text{w4rchi2} < 2$, we perform photometry on W1, W2, and W3 using the same methodology as above and pull the W4 fluxes (w4mpro) from the ALLWISE source catalog.
3. For galaxies that (a) have too low S/N for us to apply a 1σ contour to them and (b) cannot be individually resolved with a 3σ contour due to small projected separation, we pull photometry for W1, W2, W3, and W4 (w1mpro, w2mpro, w3mpro, w4mpro) from the ALLWISE source catalog.

Star subtraction is done on all SURPHOT galaxies where a confirmed star is visible within the galaxy aperture (15 galaxies). We use the stellar-dominated band with the larger PSF (W2) to define a circular aperture around the star, and this is then subtracted from the W1 through W3 fluxes. No star-subtracted galaxies are resolved in W4, so the W4 fluxes for these 15 galaxies are pulled from the ALLWISE catalog.

As the WISE absolute photometric calibration is based on profile fitting of point sources, we also apply a flux correction to account for the extended nature of our galaxies. Jarrett et al. (2013) give the corrections in magnitudes: $+0.034, +0.041, -0.030, +0.029$, for the 3.4, 4.6, 12, 22 μm bands, respectively. We convert from a magnitude correction to a flux correction using the relationship $m_{\text{apcor}} = -2.5 \log_{10} f_{\text{apcor}}$, taken from Section 2.3 of the WISE preliminary explanatory supplement.

Though most groups are local, there are several with redshifts exceeding 0.1. For the sake of consistency, we apply a k -correction to all galaxies using the low-resolution spectral templates and FORTRAN fitting code from Assef et al. (2010). Assef et al. (2010) determine low-resolution empirical SED templates from the near-ultraviolet (0.03 μm) to the mid-infrared (30 μm) that accurately reproduce galaxy properties. Their methodology is based on the assumption that every galaxy SED is some linear combination of old stellar populations, continuously star-forming populations, starbursting populations, and post-starbursting populations. We apply the Assef et al. (2010) fitting routine to our WISE W1 through W4 fluxes, using the spectral response curves from Wright et al. (2010). We note that for a small subset of the sample ($\approx 15\%$ of the full sample) the fitting routine returns a high reduced χ^2_ν value ($\chi^2_\nu > 150$); this occurs preferentially for galaxies with high S/N in W4, to which we independently fit an aperture using SURPHOT. None of the galaxies with poor χ^2_ν values are in high-redshift groups, and we expect this effect to be negligible. A majority of the galaxies in our full sample yield a $\chi^2_\nu \lesssim 1$.

Finally, 77 of the 652 galaxies either are not identified in the ALLWISE source catalog (to within $5''$) or have a negative flux measurement provided by the catalog, so these galaxies are excluded from the sample. We also impose a S/N cutoff of 2 in all four bands, as the WISE profile-fit magnitude is substituted with a 2σ brightness upper limit when the source fails to meet this S/N cutoff. Providing that the galaxy has an upper limit in only a single band, we include galaxies with $0 < \text{S/N} < 2$, but mark them as such in all color-color plots. Our final sample of galaxies, including those with upper limits in one band, is 567 galaxies (428 with reliable photometry and 139 with upper limits).

2.3. SDSS Photometry

In Section 3.5, we plot the distribution of a subsample of our galaxies in Sloan Digital Sky Survey (SDSS) color space, and

Figure 1. Left: IRAC color-space distribution of the sample of 174 galaxies from Walker et al. (2012). Right: *WISE* color-space distribution of all the galaxies common to both the Walker et al. (2012) sample and our full sample (141 galaxies). The galaxies in *WISE* color space are color-coded by their location in IRAC color space.

we derive our u , r photometry for this analysis from the DR12 SDSS photometric catalog.¹³ We use model magnitudes (“modelMag”), which implement the better of two fits (de Vaucouleurs and exponential model) in the r band to derive a matched aperture and determine the flux through all bands; modelMags are recommended for calculating the colors of extended objects.¹⁴ We apply standard Galactic extinction corrections in magnitudes following Schlegel et al. (1998). While we use the Assef et al. (2010) code to correct the mid-infrared fluxes, we k -correct our SDSS magnitudes using the IDL routine `calc_kcor.pro` from Chilingarian & Zolotukhin (2012).

3. RESULTS AND DISCUSSION

3.1. Comparison of IRAC and WISE Color Spaces

Since the available *WISE* bands [3.4 μ m (*W1*), 4.6 μ m (*W2*), 12 μ m (*W3*), 22 μ m (*W4*)] are different from the *Spitzer* IRAC bands [3.6 μ m (IRAC1), 4.5 μ m (IRAC2), 5.8 μ m (IRAC3), 8.0 μ m (IRAC4)], we cannot directly map *Spitzer* IRAC colors to *WISE* colors. In creating a distinct region of *WISE* color-color space, we need to be cognizant of the similarities and differences between the two instruments. As shown in Jarrett et al. (2011), the passbands for *W1* and *W2* closely correspond to the passbands for IRAC1 and IRAC2, though *W1* tends to be slightly bluer with respect to IRAC1, while *W2* is slightly redder with respect to IRAC2 (see Figure 1 from Jarrett et al. 2011), though this should have minimal impact on our results. Moreover, *W3* has almost no overlap with IRAC4, and the *W3* band should be more sensitive to 11.3 μ m PAH emission and 10 μ m silicate absorption in nearby star-forming galaxies, though it will be less sensitive to the stronger PAH features at 6.2 and 7.7 μ m (Jarrett et al. 2011). Thus, (a) both

W1 and *W2* and IRAC1 and IRAC2 are dominated by stellar photospheric emission while (b) *W3* will be more sensitive than IRAC4 to 11.3 μ m PAH emission in nearby galaxies and (c) *W4* has no IRAC comparison band (it is closest to the 24 μ m band on MIPS) and will have large contributions from relatively warm thermal dust emission, if present.

Since different mid-infrared bands are probes of different emission mechanisms, we can use different color combinations to separate galaxies that are actively star-forming from those that are relatively quiescent. Using IRAC colors, Walker et al. (2012) are able to separate galaxies dominated by stellar light from galaxies dominated by PAH and thermal dust emission, by plotting $\log \left[\frac{f_{8.0}}{f_{4.5}} \right]$ versus $\log \left[\frac{f_{5.8}}{f_{3.6}} \right]$. This is shown in the left panel of Figure 1. For the 141 galaxies in our full sample that we have in common with the sample of Walker et al. (2012), we are able to reproduce this same trend by plotting $\log \left[\frac{f_{12}}{f_{4.6}} \right]$

versus $\log \left[\frac{f_{22}}{f_{3.4}} \right]$, as shown in the right panel of Figure 1. Unfortunately, the two bounding canyon galaxies from the Walker et al. (2012) sample (HCG37e and HCG57h) have a low S/N in the 22 μ m band, so we are not able to directly map the IRAC canyon to the *WISE* canyon. Instead, we use the full sample to statistically define the bimodality in Section 3.2.

Comparing the two distributions, it appears that the spread of galaxies in *WISE* color space shows more scatter than their spread in IRAC color space. We attribute this in part to larger photometric errors induced by the introduction of the lower-resolution and lower-sensitivity *WISE* 22 and 12 μ m bands and the smaller aperture of the *WISE* instrument. In addition to larger photometric errors, we hypothesize that the *WISE* canyon could potentially be less prominent than the *Spitzer* canyon due in part to the inclusion of these higher-wavelength bands, which probe a different regime than the 3–8 μ m IRAC bands. It is generally assumed that 6–9 μ m features (traced by IRAC4) will be stronger in ionized PAHs (PAH⁺), while the 11.3 μ m

¹³ <http://skyserver.sdss.org/dr12/en/tools/crossid/crossid.aspx>

¹⁴ http://www.sdss3.org/dr10/algorithms/magnitudes.php#mag_model

Figure 2. *WISE* color-space distribution of our full sample. We overlay isodensity contours ($n = 5.69, 20.01$ galaxies per bin) onto our full sample, along with a line of best fit (dotted line) and the canyon bounds (dashed lines). We color-code galaxies by their location in *WISE* color-color space. We fit a canyon to the full sample by (a) determining the minimum contour level that separates the active and quiescent populations and (b) defining these regions as those lying at least 2σ above this density threshold. We determine a line of best fit for the full sample and then draw lines perpendicular to this fit and intersecting the 2σ contours at the points where the distance between the two contours is at a minimum.

feature (traced by *W3*) will be stronger in neutral PAHs (PAH^0) (Galliano et al. 2008; Wu et al. 2010; Sadjadi et al. 2015). As such, the UV-excited $7.7\ \mu\text{m}$ feature preferentially traces current star formation, while the $11.3\ \mu\text{m}$ feature preferentially traces the diffuse ISM and is often found in early-type galaxies with low star formation rates (see Cluver et al. 2013 and references therein). Moreover, there is no IRAC comparison band for *W4*, which traces relatively warm thermal dust emission.

Along this line of thought, Alatalo et al. (2014) show an “elbow” between late- and early-type galaxies in *WISE* $[W1 - W2]$ versus $[W2 - W3]$ color space and hypothesize that this result is due to the fact that galaxies transition in optical colors (quenching star formation) before IR color (shedding their ISMs, as traced by the thermal dust $22\ \mu\text{m}$ emission and $11.3\ \mu\text{m}$ neutral PAH feature), a finding also suggested in Walker et al. (2013). If the *WISE* canyon seen in compact groups is also caused in part by the shedding of the galaxies’ ISM, this could explain why the canyon is less prominent in *WISE* color space than in *Spitzer* color space. Since no IRAC bands adequately trace the $22\ \mu\text{m}$ thermal dust emission or the $11.3\ \mu\text{m}$ neutral PAH emission, ISM levels would not significantly contaminate the distribution of galaxies, potentially producing a cleaner spread in IRAC color space.

3.2. *WISE* Color-space Distribution for Full Sample

Having demonstrated the bimodality of the Walker et al. (2012) *Spitzer* sample in *WISE* color-color space, we plot the

distribution of our final sample in Figure 2. Though less pronounced than in Walker et al. (2012) and Johnson et al. (2007), there is still a visible underdensity of galaxies apparent in both samples. We note that galaxies with low S/N in *W4* potentially contaminate the *WISE* canyon at low $\log\left[\frac{f_{12}}{f_{4,6}}\right]$ color, and that these galaxies would likely shift leftward toward the quiescent population with more reliable photometry. This leftward shift would then further demarcate the canyon region, producing a greater resemblance to the bimodality in Walker et al. (2012). We emphasize that *W4* only achieves a 5σ point-source sensitivity of $\approx 6\ \text{mJy}$, so this is expected to have a tangible effect on those systems with minimal emission at $22\ \mu\text{m}$.

To define the location of the *WISE* canyon, we fit isodensity contours to the full sample. We determine the two-dimensional density function of the $\log\left[\frac{f_{12}}{f_{4,6}}\right]$ and $\log\left[\frac{f_{22}}{f_{3,4}}\right]$ colors using the IDL routine `hist_2d.pro`, adopting a bin size of 0.3×0.3 . To provide some smoothing, we interpolate the image to a grid $5 \times$ smaller by using the IDL routine `min_curve_surf.pro`. Assuming Poisson statistics, we determine the minimum contour level that separates the active and quiescent populations ($n = 12.85$ galaxies per bin). We then define the bulk of the active and quiescent populations as regions lying at least 2σ above this density threshold. With a Poissonian distribution, $\sigma = \sqrt{\mu} = 3.58$ galaxies per bin, so the contours 2σ above our minimum threshold lie at $n = 20.01$ galaxies per bin. We determine a line of best fit for the full sample and then draw lines perpendicular to this fit and intersecting the 2σ contours at the points where the distance between the two contours is at a minimum. The region bounded by these two perpendicular lines becomes our *WISE* canyon.

In Figure 2 we overlay the contours that lie $\pm 2\sigma$ ($n = 5.69$, and $n = 20.01$ galaxies per bin) from the minimum contour level separating our active and quiescent regions ($n = 12.85$ galaxies per bin). We plot the line of best fit using the dotted line and the canyon boundaries with the perpendicular dashed lines. Using this canyon definition, we color-code the galaxies as either “quiescent,” “canyon,” or “active.” Of the 567 galaxies in our full sample, 57 (10%) fall in the *WISE* canyon compared to only 5 galaxies (3%) from the Walker et al. (2012) “rotated” sample. We emphasize that a significant fraction (20 of 57) of canyon galaxies have unreliable photometry in *W4* and would likely become “quiescent” with more reliable data, so we focus much of our analysis on the 37 canyon galaxies with high S/N in all four bands. A list of results and properties for all galaxies in our full sample is shown in Table 1.

Walker et al. (2012) consider the mid-IR colors of their sample in two ways: rotated so that a straight line fit to the color-space distribution (left panel of Figure 1) becomes the axis, and unwrapped so that a curve fit to the color-space distribution becomes the axis. In both cases, the sample is shifted to a mean value of zero. As seen in the top panel of Figure 3, they define the canyon to be where the histogram is less than half its median value; the difference in the canyon bounds produced by the two methods was not statistically significant. For this work, we consider only the rotated distribution, as our *WISE* color-space distribution lacks the curvature of the IRAC distribution. Figure 3 shows the rotated mid-IR colors for the Walker et al. (2012) sample (top panel) alongside our full sample (bottom panel); we mark the

Figure 3. Rotated color-space distribution of the Walker et al. (2012) sample (top), along with our full sample (bottom). In each case, a straight line fit to the color-space distribution of the corresponding sample became the axis. For the Walker et al. (2012) IRAC sample, the dashed line indicates the median number per bin, with the horizontal dotted line half that value; the vertical dotted lines indicate the boundaries of the canyon, defined to be where the distribution is less than half the median value. Though we do not use the histogram to define the canyon, we also indicate the region corresponding to the new *WISE* canyon with vertical dotted lines.

boundaries of the canyon in both samples with the vertical dotted lines. We see that our *WISE* canyon, applied in two dimensions, agrees fairly well with the underdensity apparent in the one-dimensional distribution. This underdensity could potentially become more pronounced with more reliable photometry, as the upper-limit canyon galaxies, most of which lie in the $C_{\text{MIR_WISE}}$ bin centered at -0.05 , would shift toward more negative $C_{\text{MIR_WISE}}$ values. We also see that, although both IRAC and *WISE* show a bimodal distribution, our *WISE* sample is broadened in $C_{\text{MIR_WISE}}$ when compared to IRAC, which makes sense given that *WISE* probes a much broader range of ISM parameter space.

3.3. Star Formation Rate and Stellar Mass

The *WISE* bands have proven to be excellent probes of both star formation rate and total stellar mass content, two critical parameters needed to understand the formation and evolution of galaxies. Evolved stellar populations emit the majority of their light at near-infrared wavelengths ($1\text{--}5\ \mu\text{m}$), so both the (*W1*) $3.4\ \mu\text{m}$ and (*W2*) $4.6\ \mu\text{m}$ bands effectively trace photospheric emission from these older stars; *W1* is particularly sensitive to stellar light and can often observe luminosities on the order of L_* out to $z \approx 0.5$ (Cluver et al. 2014). The *W1* and *W2* bands are optimal tracers of the stellar mass content because they suffer minimally from extinction and can detect the Rayleigh–Jeans tail for stars hotter than 2000 K (Jarrett et al. 2013). We use Equation (9) from Jarrett et al. (2013) to derive our stellar masses: $\log\left(\frac{M_*}{L_{\text{W1}}}\right) = -0.246 - 2.100(W1 - W2)$, where *W1* and *W2* are given in magnitudes and L_{W1} is the total “in-band” luminosity, derived by multiplying the spectral luminosity, $\nu L_{3.4}$, by a factor of 22.883; as explained in Jarrett et al. (2013), this factor accounts for the difference between the total solar luminosity and the in-band values as measured by *WISE*. We convert from flux densities (Jy) to magnitudes using the relationship $m_{\text{vega}} = -2.5 \log_{10}\left[\frac{f_{\nu}}{f_{\nu 0}}\right]$, with $f_{\nu 0}$ given by 306.682, 170.663, 29.0448, and 8.2839 Jy for bands *W1*, *W2*, *W3*, and *W4*, respectively (see Table 1 in Section IV.4 of the *WISE* All-Sky Explanatory Supplement¹⁵). Similarly, we calculate global star formation rates using far-infrared thermal emission (probed by the *W4* $22\ \mu\text{m}$ band), as a sizable fraction of this emission is powered by young stars. We use Equation (2) from Jarrett et al. (2013) to calculate our star formation rates: $\text{SFR}_{\text{IR}} (M_{\odot} \text{ yr}^{-1}) = 7.50 \times 10^{-10} \nu L_{22} (L_{\odot})$, where the spectral luminosity has been normalized by $L_{\odot}$ ($3.839 \times 10^{33} \text{ erg s}^{-1}$). In all cases, luminosities are derived assuming a distance of $d = 4280 \text{ Mpc} \times z$, the same distance estimation SDSS recommends for the conversion of SDSS apparent magnitudes to absolute magnitudes.¹⁶

In Figure 4, we show $\log\left[\frac{f_{22}}{f_{3.4}}\right]$ versus $\log[M_*]$ (effectively sSFR versus stellar mass) and $\log\left[\frac{f_{22}}{f_{3.4}}\right]$ versus $\log[\text{SFR}]$ for our full sample. In both cases, the galaxies are color-coded by their location in *WISE* color–color space. We note that the *WISE* quiescent, canyon, and active galaxies from the full sample span approximately the same range in stellar mass ($\approx 10^8 - 10^{11.5} M_{\odot}$), but the quiescent galaxies (median M_* of $10^{10.59} M_{\odot}$) tend to have systematically higher stellar masses than the *WISE* canyon galaxies (median M_* of $10^{10.34} M_{\odot}$), while the *WISE* canyon galaxies have systematically higher stellar masses than the *WISE* active galaxies (median M_* of $10^{9.92} M_{\odot}$). We also find that the star formation rates of active, canyon, and quiescent galaxies overlap, but that the median of each class is shifted, with the active galaxies predictably having the highest median star formation rate ($0.65 M_{\odot} \text{ yr}^{-1}$), followed by the canyon galaxies ($0.27 M_{\odot} \text{ yr}^{-1}$) and the quiescent galaxies ($0.09 M_{\odot} \text{ yr}^{-1}$). For the full sample, our star formation rates span $\approx 0.001\text{--}10.0 M_{\odot} \text{ yr}^{-1}$.

¹⁵ http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec4_4h.html

¹⁶ <http://skyserver.sdss.org/dr12/en/help/cooking/general/getdata5.aspx>

Table 1
WISE Galaxies from Full Sample

Group	Galaxy	<i>W1</i> (mJy)	<i>W2</i> (mJy)	<i>W3</i> (mJy)	<i>W4</i> (mJy)	Morphology ^a	de Vaucouleurs Number ^a	<i>WISE</i> Class ^b	Photometry Type ^c	Upper Limit ^d
HCG 01	a	3.43 ± 0.08	2.04 ± 0.05	7.59 ± 0.22	22.50 ± 1.45	Sc	6.0	Active	3	No
HCG 01	b	4.06 ± 0.09	2.15 ± 0.05	1.96 ± 0.14	6.92 ± 1.02	E	−3.5	Canyon	3	No
HCG 01	c	3.54 ± 0.06	1.82 ± 0.04	0.67 ± 0.02	3.42 ± 6.54	E-S0	−3.4	Quiescent	2	Yes
HCG 01	d	0.95 ± 0.05	0.49 ± 0.03	0.55 ± 0.02	4.86 ± 4.78	S0	−1.9	Active	2	Yes
HCG 02	a	9.42 ± 0.09	6.11 ± 0.07	33.18 ± 0.17	87.30 ± 1.52	SBd	8.0	Active	1	No
HCG 02	b	11.90 ± 0.05	8.49 ± 0.03	79.40 ± 0.07	373.56 ± 7.72	S0-a	−1.1	Active	2	No
HCG 02	c	5.56 ± 0.06	2.94 ± 0.01	13.16 ± 0.19	8.14 ± 1.66	SABc	4.9	Active	2	No
HCG 03	a	6.92 ± 0.04	4.05 ± 0.02	17.24 ± 0.02	22.23 ± 1.44	Sc	4.6	Active	2	No
HCG 03	b	7.17 ± 0.04	3.67 ± 0.02	1.18 ± 0.06	3.85 ± 2.48	S0-a	−0.7	Quiescent	2	Yes
HCG 03	d	4.96 ± 0.02	2.52 ± 0.00	0.97 ± 0.02	3.46 ± 34.09	S0	−2.2	Quiescent	2	Yes

Notes. A machine-readable version of this table, including data for all 567 galaxies in the full sample, is provided in the electronic edition of the journal.

^a The morphological types and de Vaucouleurs numbers are from the HyperLeda database (Paturel et al. 2003a, 2003b), which accumulates morphologies from available publications and compares and combines them to determine an optimal de Vaucouleurs number and classification for each galaxy.

^b See Section 3.2 and Figure 2 for explanation of *WISE* classification scheme [Quiescent, Canyon, Active].

^c See Section 2.2 for description of photometry types.

^d This column indicates whether there is an upper limit in a single band (either *W3* or *W4*); galaxies with upper limits in more than one band are excluded from the full sample. In cases where the galaxy has an upper limit, the error in that band is set to null in the ALLWISE source catalog, and we quote the ratio of $\frac{S}{S/N}$ as the uncertainty.

(This table is available in its entirety in machine-readable form.)

Figure 4. We show $\log\left[\frac{f_{22}}{f_{3.4}}\right]$ vs. $\log[M_*]$ (left) and $\log\left[\frac{f_{22}}{f_{3.4}}\right]$ vs. $\log[\text{SFR}]$ (right) for our full sample, with the galaxies color-coded by their location in *WISE* color-color space. Galaxies with an upper limit in either *W3* or *W4* (see Figure 2) are color-coded by the same classification but plotted with crosses.

3.4. Morphology

In order to better understand the physical origins of the *WISE* canyon, in Figure 5 we plot the distribution of galaxy morphologies in *WISE* color space. The morphologies are from the HyperLeda¹⁷ database (Paturel et al. 2003a, 2003b), which accumulates morphologies from available publications and compares and combines them to determine an optimal de Vaucouleurs number for each galaxy. In our classification scheme, an average de Vaucouleurs number between -5.0 and 0.50 was assigned a morphology of E-S0/a. Similarly, $0.50-2.50 = \text{Sa-Sab}$, $2.50-4.50 = \text{Sb-Sbc}$, $4.50-7.50 = \text{Sc-Sd}$, and $7.50-10.0 = \text{Irr, Sdm}$. In concordance with Alatalo et al. (2014), we see a significant bifurcation between spirals and bulge-dominated galaxies in this distinct region of *WISE* color-color space: the quiescent region is dominated by elliptical and S0 galaxies, while the majority of Sc-Sd spiral and irregular galaxies occupy the active region. Excluding those with upper limits, the canyon galaxies between these two populations exhibit a diverse range of morphologies but are dominated in almost equal numbers by Sa-Sbc types (16 galaxies) and elliptical/S0 types (13 galaxies). The rest of the canyon galaxies with reliable photometry are a mix of Sc-Sd type (4 galaxies) and irregulars (4 galaxies). A large fraction of the upper-limit canyon galaxies (17/20 galaxies) are elliptical/S0s and would produce a canyon that is overwhelmingly early type if included in this analysis. The abundance of Sa-Sbc type galaxies in the higher-S/N canyon region is not surprising, as these galaxies tend to have brighter mid-IR blue bulges than Sc-Sd type galaxies (Jarrett 2000). When combined with their actively to moderately star-forming mid-IR green and red disks, this combination would be expected to produce green mid-IR colors indicative of moderate star formation.

Figure 5. Distribution of compact group galaxy morphologies from the full sample in *WISE* mid-IR color space. The boundaries of the canyon are marked with dashed lines. As expected, elliptical and S0 galaxies dominate the quiescent region, while Sc-Sd galaxies dominate the active region. Sa-Sbc types (16 galaxies) and elliptical/S0 types (13 galaxies) dominate the moderately star-forming *WISE* canyon region, though there are also a small number of Sc-Sd and irregular types (8 galaxies). The lone Sc-Sd galaxy in the quiescent region (IC 0107) appears to be an errant misclassification of the galaxy by the HyperLeda morphology compiler, as it morphologically resembles an elliptical galaxy.

In Figure 6, we show optical, five-color SDSS thumbnails¹⁸ alongside their *WISE* three-color thumbnails¹⁹ for all the *WISE* canyon galaxies with reliable photometry ($S/N > 2$ in

¹⁷ <http://leda.univ-lyon1.fr/leda/rawcat/a102.html>

¹⁸ <http://skyserver.sdss.org/dr12/en/tools/chart/listinfo.aspx>

¹⁹ <https://irsa.ipac.caltech.edu/applications/wise/>

Figure 6. Side-by-side comparison of five-color [ugriz] SDSS thumbnails (left) and three-color [$3.4\ \mu\text{m}$ (blue), $4.6\ \mu\text{m}$ (green), $12\ \mu\text{m}$ (red)] composite WISE thumbnails (right) of all the $S/N > 2$ galaxies in the WISE canyon that fall within the SDSS footprint (31 galaxies). The size scale in each pair is identical, and the scales range from $30''$ to $360''$ over all thumbnails. The median PSF (r band) of the SDSS cutouts is $1''.3$, while the typical PSF ($3.4, 4.6, 12\ \mu\text{m}$ bands) for the WISE cutouts is $8''.5$. In the WISE images, red indicates active star formation while blue indicates quiescence, whereas the opposite is true in the SDSS images.

Figure 6. (Continued.)

all four bands) in the SDSS DR12 footprint (31 of 37 total canyon galaxies). Of the 31 reliable canyon galaxies within the SDSS footprint, 11 show visible signs of gravitational interaction with a neighboring companion in their *WISE* thumbnail. Moreover, the combination of mid-IR blue bulges and mid-IR red star-forming disks is apparent in a number of the *WISE* thumbnails (for example, HCG 22c, HCG 45a, HCG 69a, HCG 71a, HCG 88a, NGC 0070, NGC 4274). Interestingly, several galaxies show the opposite color combination (mid-IR red nucleus and mid-IR blue outskirts), including HCG 37b, NGC 4117, and NGC 4314.

3.5. *WISE*-SDSS Color Space

As seen in Figure 7, we also confirm a relation between $\log\left[\frac{f_{12}}{f_{4.6}}\right]$ and $[u - r]$ color for compact group galaxies, a relation first noted for Galaxy Zoo sources in Alatalo et al. (2014). They find a significant bifurcation between late-type (blue contours) and early-type (red contours) galaxies; the green valley galaxies (cyan contours) appear at the elbow of the two distributions. The Alatalo et al. (2014) contours are derived by plotting $\approx 50,000$ field galaxies in this region of color space, which are characterized as either “early,” “late,” or “green valley” objects in Galaxy Zoo. We plot the 407 galaxies from the full sample that fall within the SDSS footprint and overlay

the same contours as Figure 1(f) in Alatalo et al. (2014), now uncorrected for intrinsic extinction. Alatalo et al. (2014) originally correct for intrinsic extinction using the $E(B - V)_{\text{stars}}$ from the Oh et al. (2011) OSSY catalog, which is then converted to an extinction measure at the rest wavelength of the galaxy. The OSSY database is derived from the SDSS DR7 spectral catalog, and only $\approx 2/3$ of our sample has SDSS spectral data; thus, we are not able to correct for intrinsic extinction following the methodology from Alatalo et al. (2014). As a subset of our sample tends to be both dusty and actively star-forming, correcting for intrinsic extinction would preferentially shift our active population toward lower $[u - r]$ color, and the kink in the distribution would become more pronounced.

When comparing the photometry, we find an offset between the Galaxy Zoo $[W2 - W3]$ colors and our compact group $[W2 - W3]$ colors. The Galaxy Zoo magnitudes are composed largely of the *w2gmag* and *w3gmag* parameters in the ALLWISE source catalog, whose elliptical apertures are scaled from the 2MASS extended source catalog apertures. Specifically, the ALLWISE *gmag* aperture semimajor axes are 1.1 times the 2MASS XSC K_s circular semimajor axes. When directly comparing the subsample of our compact group galaxies that are also Galaxy Zoo objects, we find a net offset of ≈ 0.3 – 0.4 mag between the two samples. We attribute this

Figure 7. Distribution of compact group galaxies in $\log \left[\frac{f_{12}}{f_{4.6}} \right]$ vs. $[u - r]$ color, with contours (now uncorrected for intrinsic extinction) from Alatalo et al. (2014) overlaid. The galaxies are color-coded by their location in *WISE* color-color space; galaxies with an upper limit in either *W3* or *W4* (see Figure 2) are color-coded by the same classification but plotted with crosses. We confirm a bimodality between morphologically classified early-type (red contours) and late-type (blue contours) galaxies, first seen for field galaxies in Alatalo et al. (2014), but here for compact group galaxies, with a majority of our *WISE* canyon galaxies falling at the elbow of the two distributions. We also note a dearth of *WISE* canyon galaxies within the optical green valley (cyan contours).

offset to a difference in aperture type: the *gmag* elliptical apertures are determined using solely the $2.159 \mu\text{m}$ 2MASS *K_s* image, while are custom 1σ – 3σ contour apertures are determined using an averaged, λ^{-1} weighted reference image composed of the 3.4 , 4.6 , and $12 \mu\text{m}$ images. Our offset is consistent with the findings of Cluver et al. (2014), who quantify the difference between *WISE* *gmag* and isophotal photometry and determine a shift of ≈ 0.2 – 0.4 mag. The *gmag* apertures can also be contaminated by neighboring sources, which likely produces higher *gmag* values for faint sources when compared directly to the isophotal photometry (Cluver et al. 2014). Nevertheless, the shift is not significant with regard to our conclusions, and we note the same bifurcation between “active” compact group galaxies (dominated by late-type Sc–Sd galaxies; see Figure 5) and “quiescent” compact group galaxies (dominated by early-type E/S0 galaxies). We also find that the *WISE* IR canyon galaxies cluster near the “elbow” between the early-type (lower right red contours) and late-type (upper left blue contours) galaxy distributions, though they do tend to span a larger range in $[W2 - W3]$ color. We also note a dearth of canyon galaxies within the optical green valley (cyan contours), reconfirming that *WISE* infrared canyon galaxies *do not fall in the optical green valley*. Instead, as argued in Walker et al. (2013), we confirm that the majority of our *WISE* canyon galaxies tend to be optically redder than typical green valley objects in Galaxy Zoo, falling on or near the red sequence.

4. SUMMARY AND CONCLUSIONS

We perform custom photometry on a comprehensive sample of 163 compact groups and produce a catalog of 567 compact group galaxies in all four *WISE* bands. Within this sample, we present the identification of 37 moderately star-forming *WISE* canyon galaxies with reliable photometry that lie in a distinct region of *WISE* $\log \left[\frac{f_{12}}{f_{4.6}} \right]$ versus $\log \left[\frac{f_{22}}{f_{3.4}} \right]$ color-color space. Canyon galaxies are severely underrepresented in the previous *Spitzer* sample, and the small number statistics prevent an understanding of the dominant evolutionary mechanisms at play. With this enlarged sample, it should be possible to begin statistically characterizing the properties of the *WISE* canyon galaxies and to examine what processes may be causing their accelerated evolution. We also note that, despite the *WISE* canyon region being less pronounced than the *Spitzer* IRAC canyon, we can also utilize this *WISE* color space to separate galaxies dominated by stellar light from galaxies dominated by PAH and thermal emission. The creation of a photometric catalog could aid future studies seeking to characterize the properties of these unique galaxies and their accelerated evolution.

We also note distinct trends between *WISE* classification (quiescent, canyon, active) and both stellar mass and star formation rate. Though the classes span approximately the same range of stellar masses, the *WISE* quiescent class tends to have systematically higher stellar masses than the canyon class, while the canyon class has systematically higher stellar masses than the active class. The opposite is predictably true for star formation rate: though the classes overlap in SFR space, the active class has the highest median SFR, followed by the canyon class and the quiescent class.

Similar to Alatalo et al. (2014), we find that compact group galaxies also exhibit a bimodality between early- and late-type galaxies in *WISE* $\log \left[\frac{f_{12}}{f_{4.6}} \right]$ versus $\log \left[\frac{f_{22}}{f_{3.4}} \right]$ color-color space, with a plurality of *WISE* narrow canyon galaxies being of type Sa–Sbc. However, we note that the canyon between spiral and bulge-dominated galaxies does not correspond to the optical green valley and confirms the results from Walker et al. (2013) that a majority of *WISE* canyon galaxies tend to be optically redder.

Ultimately, this statistical sample provides a means to address how galaxies are transformed in the high-density and dynamically evolving compact group environment, and consequently what impact this key environment has on galaxy evolution and hierarchical formation. A number of processes could be responsible for this accelerated evolution—possibilities include briefly enhanced star formation due to a tidal inflow of gas, rapidly quenched star formation to the tidal removal of gas, or strangulation if cool filaments of gas are not able to refuel the system. Determining the relative importance of these and other mechanisms is essential to understanding how the gas is processed in these groups, which has a direct impact on the resulting merger products.

This publication makes use of data products from the *Wide-field Infrared Survey Explorer*, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration.

Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S.

Department of Energy Office of Science, and the Participating Institutions. SDSS-IV acknowledges support and resources from the Center for High-Performance Computing at the University of Utah. The SDSS Web site is www.sdss.org.

C.S.Z. would like to sincerely thank the anonymous referee for their thorough feedback throughout the review process. She would also like to thank the Virginia Space Grant Consortium and the University of Virginia College of Arts and Sciences for support.

S.C.G. thanks the Natural Sciences and Engineering Research Council of Canada for support.

APPENDIX

A.1. Canyon Bounds

Quantitatively, we define our canyon zone to be where

$$\begin{aligned} \text{ywise} &\geq (0.01866 - 1.885 \times \text{xwise}) \wedge \text{ywise} \\ &\leq (0.7844 - 1.885 \times \text{xwise}), \end{aligned}$$

where $\text{xwise} = \log [f22/f3.4]$ color and $\text{ywise} = \log [f12/f4.6]$ color.

REFERENCES

- Alatalo, K., Cales, S. L., Appleton, P. N., et al. 2014, [ApJL](#), **794**, L13
- Aniano, G., Draine, B. T., Gordon, K. D., & Sandstrom, K. 2011, [PASP](#), **123**, 1218
- Appleton, P. N., Xu, K. C., Reach, W., et al. 2006, [ApJL](#), **639**, L51
- Assef, R. J., Kochanek, C. S., Brodwin, M., et al. 2010, [ApJ](#), **713**, 970
- Barton, E., Geller, M., Ramella, M., Marzke, R. O., & da Costa, L. N. 1996, [AJ](#), **112**, 871
- Barton, E. J., de Carvalho, R. R., & Geller, M. J. 1998, [AJ](#), **116**, 1573
- Chilingarian, I. V., & Zolotukhin, I. Y. 2012, [MNRAS](#), **419**, 1727
- Cluver, M. E., Appleton, P. N., Boulanger, F., et al. 2010, [ApJ](#), **710**, 248
- Cluver, M. E., Appleton, P. N., Ogle, P., et al. 2013, [ApJ](#), **765**, 93
- Cluver, M. E., Jarrett, T. H., Hopkins, A. M., et al. 2014, [ApJ](#), **782**, 90
- Galliano, F., Madden, S. C., Tielens, A. G. G. M., Peeters, E., & Jones, A. P. 2008, [ApJ](#), **679**, 310
- Hickson, P. 1982, [ApJL](#), **255**, 382
- Hickson, P., de Oliveira, C. M., Huchra, J. P., & Palumbo, G. G. 1992, [ApJL](#), **399**, 353
- Jarrett, T. H. 2000, [PASP](#), **112**, 1008
- Jarrett, T. H., Cohen, M., Masci, F., et al. 2011, [ApJ](#), **735**, 112
- Jarrett, T. H., Masci, F., Tsai, C. W., et al. 2013, [AJ](#), **145**, 6
- Johnson, K. E., Hibbard, J. E., Gallagher, S. C., et al. 2007, [AJ](#), **134**, 1522
- Konstantopoulos, I. S., Maybhat, A., Charlton, J. C., et al. 2013, [ApJ](#), **770**, 114
- Lang, D. 2014, [AJ](#), **147**, 108
- Oh, K., Sarzi, M., Schawinski, K., & Yi, S. K. 2011, [ApJS](#), **195**, 13
- Paturel, G., Petit, C., Prugniel, P., et al. 2003a, [A&A](#), **412**, 45
- Paturel, G., Theureau, G., Bottinelli, L., et al. 2003b, [A&A](#), **412**, 57
- Reines, A. E., Johnson, K. E., & Goss, W. M. 2008, [AJ](#), **135**, 2222
- Sadjadi, S., Zhang, Y., & Kwok, S. 2015, [ApJ](#), **807**, 95
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, [ApJ](#), **500**, 525
- Tzanavaris, P., Gallagher, S. C., Hornschemeier, A. E., et al. 2014, [ApJS](#), **212**, 9
- Tzanavaris, P., Hornschemeier, A. E., Gallagher, S. C., et al. 2010, [ApJ](#), **716**, 556
- Walker, L. M., Butterfield, N., Johnson, K., et al. 2013, [ApJ](#), **775**, 129
- Walker, L. M., Johnson, K. E., Gallagher, S. C., et al. 2010, [AJ](#), **140**, 1254
- Walker, L. M., Johnson, K. E., Gallagher, S. C., et al. 2012, [AJ](#), **143**, 69
- Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, [AJ](#), **140**, 1868
- Wu, Y., Helou, G., Armus, L., et al. 2010, [ApJ](#), **723**, 895