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CLASH: GALAXY FORMATION CONSTRAINTS FROM DISTANT SPATIALLY EXTENDED STRONGLY LENSED GALAXIES

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ABSTRACT

Opening statement on fundamental questions of galaxy formation, and the bifurcation of a couple basic scenarios. These scenarios lead to predictions, including fairly nuanced or sophisticated measurements that one can make of individual galaxies, such as metallicity tracers and the like. For very distant or intrinsically faint galaxies these are very difficult observations to make, and are more suited for the GSMT or JWST eras. An opening foray can be made through a detailed exploration of internal variations of the stellar populations. While impractical when galaxies at high redshift are only modestly resolved by *HST*, we can take advantage of the significant 10-100x stretching and reprojection of galaxies that are lensed by foreground massive galaxy clusters. We report on a pilot analysis of twenty such objects, between redshifts $z \sim 1-3$, lensed by clusters targeted by the CLASH survey, and therefore with 16 *HST* bands of ~ 1 orbit depth each and spanning NUV through the NIR. Because the lensing process is fully stochastic, this is essentially a fortuitously discovered and random sample of distant lensed galaxies. We do sophisticated stellar population synthesis analysis across many resolution elements of each galaxy, and derive the spatial variance in key model parameters. We find some cool stuff.

Subject headings: gravitational lensing

1. INTRODUCTION

The goal of this project is to characterize the stellar populations of high-redshift lensed galaxies and contrast them with a lower-redshift comparison sample. By separately fitting the SEDs of spatially resolved galaxy segments, we aim to characterize the distribution of star formation in high-z galaxies, identify passively evolving stellar components, and if possible compare the metallicities of the various components to identify the source of the star-forming gas. In a separate but similar project, we will use lensed, edge-on star-forming galaxies with clear dust lanes to characterize the dust absorption spectrum in these galaxies. For both projects, we will make use of the full set of 16-band HST photometry that is being acquired by the CLASH collaboration.

The tasks described in §2-4 are necessary for both projects. The SED-fitting project with further require running the ISEDFIT model of J. Moustakas in order to obtain stellar population information. In contrast, the dust-SED fitting will be an empirical comparison of the dust-obscured and non-dust-obscured regions of individual galaxies, and therefore does not require the use of ISEDFIT. I (G. Graves) therefore propose that the SED-fitting project be led by L. & J. Moustakas, while the dust-SED project be led by myself, but this is of course open to discussion and may evolve as the project progresses.

1.1. *Gradients in Spiral Galaxies*

Metallicity gradients: I think it is pretty well established that spiral galaxies have substantial metallicity gradients, with metal-rich centers and metal-poor outer parts. People have done this looking at stellar metallicity gradients with colors in other galaxies (e.g. **?**), with stellar spectra in our own galaxy (e.g. **?**), and by mapping the metallicity gradients of HII regions in star-forming galaxies (e.g. **?**).

Age gradients: There are multiple studies that suggest that spirals also have significant age gradients, with older stars in the center and younger stars in the outer parts. e.g., Bell & de Jong (2000) fit SEDs to radially resolved optical and near-IR photometry and find the centers of galaxies to be old and metal-rich, while the outer parts are younger and more metal-poor. Kauffmann et al. (2006) find that many massive bulge-dominated galaxies have blue outer regions, which appear to show residual star formation even after star formation has ceased in the inner part of the galaxy.

1.2. *Gradients in Early Type Galaxies*

(Somerville et al. 2003), (**?**), (**?**).

Metallicity gradients: It is well-established that early type galaxies show strong metallicity gradients, with metal-rich centers and metal-poor outer parts. The SAURON team (Scott, Cappellari et al. 2009) recently published this in an interesting and somewhat novel way—plotting [Z/H] as a function of the local escape velocity in the galaxy (essentially a radial gradient, with high Vesc in the center). There are many other studies that show similar things, both with spectral absorption line strengths and colors.

Age gradients: These are more debated. The Scott et al. (2009) paper mentioned above find age gradients that are flat in some galaxies, while other show youngish central ages and older ages farther out. Another relevant paper is Sanchez-Blazquez et al. (2007), who find weak or no age gradient in 10/11 early types, while one have a very young center. Interestingly, the weak positive age gradients, combined with the negative metallicity gradients, means that the age-metallicity degeneracy acts to keep galaxy color (and line-strength) gradients weaker

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than they otherwise might be.

Abundance ratio gradients: There do not seem to be strong [alpha/Fe] gradients in early types. In the papers quoted above, Scott et al. (2009) find no [alpha/Fe] gradients and Sanchez-Blazquez et al. (2007) find no gradients, weak positive gradients, or weak negative gradients in their galaxies.

Gradients beyond the half-light radius: In general, these studies do not go beyond the half-light radius of the galaxy. Some work that I am doing right now tracing stellar population gradients out to 2-3 Reff essentially agrees with these studies: Age gradients vary from galaxy-to-galaxy, are usually weak, but with some galaxies showing young cores. All galaxies show strong negative gradients in total metallicity. [alpha/Fe] varies little with radius. Interestingly, carbon-enhancement ([C/Fe]) seems to scale strongly with radius—galaxies have much higher [C/Fe] in their centers that in their outskirts.

At high redshift – stuff happens.

It is of course much harder to study population gradients at high redshift. Rigby et al. (2011) and Wuyts et al. (2010) have SEDs and spectroscopy for a lensed galaxy at z=1.7, but don't try to extract spatially-resolved information. There was a Rigby HST proposal in Cycle 18 to do resolved SED fitting for a lensed arc (might well be the same one) which I think got time, but I don't see the paper out yet.

Theory

Spiral galaxies: I don't know much about formation models for spiral galaxies. Bell & de Jong (2000) propose a scenario in which star formation happens early and rapidly in high-density regions of the galaxy (i.e., the center) and proceeds more slowly out at large radius where the gas densities are low, hence leaving low-lever star formation in the outer parts of the galaxy at late times. There is a huge literature on the Milky Way star formation history and detailed chemical evolution models with which I am not very familiar. Some names that spring to mind are Brad Gibson, Rok Roskar, Daisuke Kawata, Chiaki Kobayashi. I'm sure I'm missing some big ones.

Early-type galaxies: There are limited numbers of chemical evolution models for early type galaxies (Gibson et al. 2007, Pipino et al. 2010), and they tend to be trying to reproduce existing observations, not making strong new predictions. An interesting recent paper is Oser et al. (2010). They model massive early type galaxies using a hydro-code super-posed on a zoom-in of a cosmological N-body simulation. Their galaxies wind up containing two sub-populations of stars, those that formed "in situ" in the massive halo, and those that formed in satellites outside Rvir of the main halo, which were then accreted at later times. The in situ stars dominate the central part of the galaxy, while the accreted stars wind up at much higher radius, thus setting up a strong gradient in the origin of the stars. Interestingly, both the in situ stars and the accreted stars tend to be old. There is often a little dribble of residual in situ star formation in their models of less massive galaxies, which would tend to make the central population younger. Also, you'd expect strong differences in the metallicities of the two components, with the in situ stars showing much higher metallicities than those that were accreted from small satellites, due to the mass-metallicity relation and the greatly reduced ability of small galaxies to hold onto metal-enriched SN ejecta.

The power of strong gravitational lensing as a tool towards a broad range of astrophysical discoveries. (Reference to some lensing school notes, eg the Saas Fee lectures). The lensing object (REF), magnified background sources (**?**), and indeed for cosmology (Coe & Moustakas, submitted). Lots of references here for background, nothing too profound.

To these ends, since the first strong lens was discovered by **?**, both serendipity and systematic programs have uncovered several hundred strong lenses by the present day. Broadly speaking, these have been found through one of two techniques, whether serendipitous or through a structured and pre-determined strategy. The first exploits the remarkable visual geometry of lenses in space- or ground-based imaging data (e.g. MDS **?**, EGS **?**, SL2S **?**, HAGGLeS **?**). The second is spectroscopic, and relies on the observation of "anomalous" spectroscopic features.

This latter approach was pioneered by **?**, and has come to spectacular fruition by the Sloan Lens ACS (SLACS) Survey (**?**), which has confirmed some one hundred new strong galaxy-galaxy lenses by *Hubble* imaging follow-up to spectroscopically identified candidates. While the efficiency afforded by the Sloan spectroscopic database is high, lenses have been uncovered through regular ground-based spectroscopic observations (e.g. **?**). In this paper we report on similarly discovered lenses, in several distant galaxy clusters, which all happen to be from the X-ray flux-limited Massive Cluster Survey (MACS) sample of **?**.

The observations are described in the following section, followed by a more detailed presentation of the lenses and the available data. We end with a discussion of the lensing rates implied by these discoveries, how other surveys may fare, and the general utility of such lenses. All magnitudes are given in AB, and where relevant we adopt a concordance cosmology.

2. TARGET SELECTION

We need to identify lensed sources that are bright enough and extended enough for resolved SED analysis. Targets should also have spectroscopic redshifts. Two types of targets are particularly of interest: those with obvious clumpy structures that are ideal for resolved SED fitting, and those that appear to be lensed edge-on star-forming galaxies with strong dust lanes.

Genevieve has made a first pass at identifying candidates for analysis. She combined the available spec-z catalogs with the HST images (using the 30mas scale images when available) for all clusters that currently have both spec-z's and reduced HST imaging. These include the following clusters: Abell 383, Abell 2261, MACS 1149, MACS 1206, MACS 2129, and RXJ 1347. Of these, Abell 2261 and MACS 2129 did not have any spec-z measurements for arcs, only for cluster members. Candidate targets are listed in Table 2 and illustrated with thumbnails in Figure 1.

Ingredients:

1. HST detection image of each cluster.
2. Color images of each cluster (e.g., the beautiful new press release images).

TABLE 1

RA	Dec	Cluster	$m_{\rm filter}$	$\theta_{\rm E}$	$z_{\rm lens}$	$z_{\rm source}$	Notes
J2000			AB	arcsec			
00:25:23.487	−12:19:42.8	MACS J0025.4−1222	30.0	1.0 ± 0.3	0.582	2.047	
17:20:06.416	+35:35:26.3	MACS J1720.3+3536	$r_{\rm SDSS} = 20.6$	1.0 ± 0.3	0.384	2.132	
17:20:18.486	+35:37:12.8	MACS J1720.3+3536	$r_{\rm SDSS} = 19.1$	1.0 ± 0.3	0.385	2.787	
21:29:19.973	−07:42:18.2	MACS J2129.4−0741	$r_{\rm SDSS} = 21.6$	1.0 ± 0.3	0.594	1.211	AGN Source

TABLE 2
CANDIDATE TARGETS

Cluster	z^*	RA	δ	Notes
Abell 383	1.010	42.00985	-3.53102	Long, extended arc with clumpy sub-structure
Abell 383	2.550	42.00908	-3.53347	Multiply imaged extended blue arc, clumpy
MACS 1149	1.491	177.39698	22.39601	Spiral galaxy smeared throughout the cluster
MACS 1149	1.894	177.40605	22.39247	Small multiply imaged galaxy. Looks like it has a central bulge and a disk, both blue. Could also be a disk + bright star-forming knot.
MACS 1149	2.497	177.39284	22.40323	Multiply-lensed, relatively bright. Possibly a clumpy disk.
MACS 1206	1.033	181.54473	-8.80121	Very large, bright star-forming galaxy with strong dust lane
MACS 1206	1.036	181.54701	-8.79536	Extended, bright star-forming galaxies with strong dust. Possibly another image of the galaxy above?
MACS 1206	1.033	181.54452	-8.78765	Clumpy, reddish galaxy with distinct knots and possible tidal tails.
MACS 1206	2.538	181.55238	-8.79536	Stripey star-forming galaxy with strong dust lanes. Lensed and very extended.
MACS 1206	1.008	181.57103	-8.80168	Patchy red and blue galaxy. Not sure if it is lensed.
MACS 1206	3.030	181.56281	-8.79589	Patchy blue galaxy. Another patch with $z = 3.035$ right next to it.
MACS 1206	3.038	181.56055	-8.80902	Two more patchy blue galaxies, one at $z = 3.038$ and one at $z = 3.034$. Possibly multiple images of the galaxy above?
RXJ 1347	0.785	206.87964	-11.74411	Red lensed galaxy with a small blue dot/clump. Possibly a cosmic ray?
RXJ 1347	0.806	206.88336	-11.74501	Star-forming galaxy with dust lanes and blue clumps.
RXJ 1347	0.906	206.89103	-11.74740	Relatively smooth lensed galaxy with an exponential light profile. Maybe not so interesting.
RXJ 1347	*1.700*	206.88742	-11.75761	Lensed, smooth light profile, odd pinky-blue color (star formation plus dust?)
RXJ 1347	*1.750*	206.88255	-11.76426	Lensed star-forming galaxy, bright center, possible dust lane.
RXJ 1347	*1.750*	206.87200	-11.76108	Strongly lensed, extended arc, blue clumps and dust.
RXJ 1347	*2.500*	206.87204	-11.76534	Extended low surface brightness arc, very red and smooth
RXJ 1347	*3.000*	206.87355	-11.76827	Bright, compact, strongly lensed.

* Redshifts in italics may be unreliable. They are rounded off to the nearest 0.05 and seem to cluster at similar values. We need to check these.

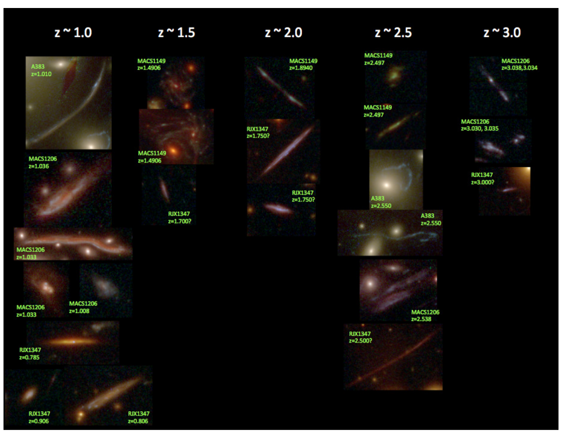

FIG. 1.— Candidate targets for SED analysis, sorted by redshift. For each candidate, the lensing cluster and redshift are indicated. More information about each candidate can be found in Table 2 including coordinates for locating each source.

3. Catalogs of spectroscopic redshifts and target coordinates.

Tasks:

1. Put the spec-z catalogs into the format of DS9 *.reg files.
2. Identify lensed background sources that have spec-z's. Focus on those with interesting clumpy features, light distributions, or dust lanes.
3. Follow up with other team members about the source of the suspect spec-z's in RXJ 1347.
4. Create a ranked list of candidates for analysis.
5. When final targets are chosen, double-check the source of the spec-z to make sure the redshift is correct and reliable.

3. IMAGING DATA

We will use the CLASH multi-band images that have been matched, registered, and resampled to a common 30mas pixel grid. Our SED analysis measures the relative fluxes in different bands over matched apertures; it is critical to have well-matched apertures in all filters. Apertures will be defined in the summed "detection" images, then applied in each individual filter.

The existing images have been resampled to a common scale, but have different intrinsic resolution due to PSF variations. To make a fair comparison between the various filters without aperture problems, we will convolve the higher resolution (compact PSF) images to match the lowest resolution images in our filters. **Open question:** How do we want to do the error analysis? Do we need to make some kind of error map and track the correlated errors generated by the PSF convolution?

Background contamination from the BCG and other cluster members may be a problem. It might be best to do the final analysis on images in which the BCG and other bright cluster members have been modeled and subtracted. Leonidas has suggested that Sara Ogaz's thumbnails of individual galaxies and their GALFIT models might be useful here. One possibility is to add this to the InterCLASH interactive tool that he and James Davies developed over the summer. We may also want to make use of Marc Postman's careful fits to the extended BCG light.

Ingredients:

1. The 16 individual drizzled images for each cluster containing a target. **NOTE:** 30mas images do not yet exist for all observed clusters!
2. The weight map for each image.

3. The PSF (average over the field of view? as a function of location?) for each individual filter.
4. Sara's thumbnail images and GALFIT model fits to individual cluster members.
5. Marc's extended BCG fits for careful background subtraction.

Tasks:

1. Obtain the PSF for each filter.
2. Convolve the images to a common effective resolution.
3. Construct error maps that treat the correlated errors from drizzling and PSF convolution in a reasonable way.
4. Implement a way to create images in which the BCG and other bright cluster members have been subtracted. Create these images and use them (instead of? in addition to?) the raw images themselves.

4. APERTURES OF UNUSUAL SIZE/SHAPE

Once the images have been resampled onto matching pixel grids and convolved to have the same effective resolution, we can define apertures of any size or shape by designating which pixels should be included in each aperture. This process involves deciding where to draw the boundaries for each aperture, producing a list of pixels that belong in each aperture, then computing the summed flux and corresponding error values for each filter in each aperture.

Chien Peng has written tools that will be useful for this. There are two relevant programs. The first, *ds9poly.c*, is a tool for defining polygons interactively in DS9. The second, *fillpoly.f*, takes the polygon output from ds9poly and produces a list of coordinates for all of the pixels that fall inside that polygon. A description of these tools can be found here on his "Bad Pixel Masking FAQ" page.

Once apertures have been defined and the pixels corresponding to each aperture have been tabulated, we can sum the flux in the constituent pixels for each aperture and compute errors on the summed aperture fluxes. **NOTE:** We have to figure out how to deal with the correlated errors in adjascent pixels due to drizzling and PSF convolution.

Ingredients:

1. The routines *ds9poly.c* and *fillpoly.f* from Chien Peng's website.
2. Re-sampled, PSF convolved, (possibly BCG and cluster member subtracted) images for the cluster in each filter.
3. Error maps for each filter(?).

Tasks:

1. Download, install, and test *ds9poly.c* and *fillpoly.f.*
2. Choose apertures.
3. Run *ds9poly* and *fillpoly* to create pixel lists for each aperture.
4. Write an IDL code to take the 16 input *.fits images and aperture pixel lists and produce summed fluxes and errors in each band for each aperture.

5. STELLAR POPULATION SED FITTING

The first project goal is resolved SED fitting of stellar populations in lensed galaxies. This project may present the resolved fitting of invidual objects on their own, or may aggregate the properties of many objects to study resolved stellar populations at several different redshifts.

Once 16-band photometry has been computed in a given aperture, we will use John's ISEDFIT code to fit the aperture SEDs. Currently, John's code is set up to run grids for several different stellar population models: Bruzual-Charlot 2003, Maraston 2005, and Conroy's Flexible Stellar Population Synthesis (FSPS). Comparing results from the various models will help constrain the systematics of using different underlying models.

There are several quantities of interest in the model results. The models will measure $M_\star$ values for the various galaxy sub-components. To interpret these masses, we will need to know the magnification due to cluster lensing. These values can be obtained from the strong lensing analysis of the clusters. Question: does the magnification vary across the arcs? Is this something we can hope to constrain?

ISEDFIT also produces best-fitting values of age, Z, star-formation timescale τ, and dust reddening $E(B-V)$. It will be interesting to compare the ages and star-formation timescales of different galaxy components as measured in the various apertures. One goal is to constrain whether star formation in galaxies proceeds "inside out" or "outside in". Tying the different apertures to actual locations in the unlensed source will probably require deprojecting the lensed galaxies back to the source plane. This information can presumably be obtained from the strong lensing analysis by other team members.

Another interesting aspect of the resolved stellar population analysis will be to look for the presence of old stellar components, particularly in high redshift galaxies. The detection of truly passive sub-components of high redshift galaxies might allow us to say interesting things about bulge formation in galaxies.

The stellar population information is sensitive to various age/Z/dust degeneracies. It will be important to track and quantify these degeneracies, probably by looking at the full χ^2 distribution in multi-dimensional parameter space. In particular, I think it will be interesting to explore the co-dependence of pairs of parameters (e.g., age-Z, age-τ, age-dust) while marginalizing over other parameters.

Depending on how bad the Z-related degeneracies are, it might be possible to constrain the metallicities of different galaxy sub-components. Of particular interest would be to compare the Z values of the most active star-forming regions with those of the older stellar components to look for evidence of the source of the gas in the star-forming knots. Star formation that is triggered through pristine gas accretion or merging with gas-rich low-mass (and therefore low-Z) companions could produce low-Z star-forming regions, while ongoing quiescent star formation or major mergers (with more equal mass and therefore more equal Z companions) would presumably result in higher-Z star forming regions.

Ingredients:

1. The ISEDFIT code package, with reasonable pre-

computed model grids.
2. The total aperture photometry from §4, along with errors.
3. Magnification maps and source plane reconstructed morphologies for the lensed galaxies from the strong lensing analysis by other team members.

Tasks:

1. Decide which model grids to use for ISEDFIT. If we want anything other than the 3 pre-computed models for ISEDFIT, we will need to produce them.
2. Run ISEDFIT on the aperture photometry from §4.
3. Explore the χ^2 distribution in the multi-dimensional input parameter space in order to constrain the various stellar population modelling degeneracies.
4. Do science!!!

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REFERENCES

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