Astro2020 Science White Paper

Characterizing the Assembly of Galaxy Cluster Populations Over Cosmic Time

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation

☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics

☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments

☒Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

Principal Author:

Name: Michael Pierce
Institution: University of Wyoming
Email: mpierce@uwyo.edu
Phone: 307-766-6102

Co-authors: (names and institutions)

Marie Lemoine-Busserolle (Gemini Observatory)

Abstract (optional):

The next generation of extremely large ground-based telescopes (ELTs) offers the opportunity to quantify the assembly history of galaxies via the traditional scaling relations such as the Tully-Fisher relation (TF) for spiral galaxies and the fundamental plane (FP) of elliptical galaxies. A characterization of elliptical galaxy evolution should include: 1) construction of the FP vs redshift and environment, 2) establishing the chemical evolution of and downsizing of star formation within the progenitors of today's cluster populations, 3) determination of the relative role of "wet" vs. "dry" mergers in the formation of elliptical galaxies and 4) establishing the statistics of multiple supermassive black holes within the most massive elliptical galaxies. Accomplishing these goals will require an extensive, targeted survey of the galaxy populations within the field and clusters using a "layer-cake" approach that makes use of a broad range of telescope apertures. Small, 3-4-meter class telescopes will be used to characterize the local populations down to luminosities well below L*, mid-sized 8-meter class telescopes will be used to characterize the $0.5 < z < 1.0$ populations and the ELTs will eventually be used to explore the $1 < z < 2$ populations once they come on line. Over the next decade the results of this effort will form the foundation for studies of galaxy evolution and assembly that constitute several of the key science goals for the next generation of ELTs.

Scientific Goals

A strong science case can be made for a targeted program directed towards characterizing the assembly of galaxies in anticipation of the development of the ELTs [26]. It is now clear that the peak of the star formation occurs near redshifts of 2 [5] and it appears that substantial hierarchical merging continues to z ~ 1 at which point the familiar galaxy morphologies are emerge [31, 17]. In addition, the fraction of star forming galaxies within rich clusters increases with z [4, 35] implying that substantial assembly and evolution is occurring over all environments. The assembly process continues down to relatively modest redshifts (z ~ 0.3) and shows clear evidence of "down-sizing" with the evolution progressing more rapidly for the more massive galaxies [2, 15, 10, 34]. While the instantaneous merger rate as a function of z can be estimated from imaging data alone [2], spatially-resolved spectroscopy of galaxies is necessary to characterize its consequences. The assembly of disk systems is thought to be characterized by a series of minor mergers that preserve their disk morphologies as they are assembled and this is reflected in the spread of metal abundances of within late-type galaxies [36] and the presence of stellar streams from the most recent accretion of dwarf satellites. In contrast, the assembly of ellipticals is believed to progress through primarily major mergers resulting in the structural scaling relations exemplified via projections of the fundamental plane (FP; [6, 8]).

Quantifying the Assembly and Evolution of Elliptical Galaxies

The general consensus is that elliptical galaxies have formed through major mergers [28] yet we might still expect they will contain a fossil record of their assembly. In particular, if ellipticals form through both the mergers of gas-rich galaxies (so-called "wet" mergers) and through the mergers of essentially gas-free galaxies (so-called "dry" mergers) [12] it is plausible that this could be reflected in subtleties in the fundamental plane.

An extensive survey of the FP has been underway for some time that is aimed at addressing some of these questions through the accumulation of extensive, high-quality photometric and spectroscopic data sets for the elliptical populations within ~ 40 nearby clusters [WFPS; 20]. Here we show some of the data, some of the preliminary results, and discuss the prospects for extending these efforts to high-z using (eventually) the ELTs. The primary goal of the WFPS was to acquire high quality photometric and spectroscopic data in order to examine whether the assembly history of elliptical galaxies was reflected in the various projections of the FP. A few of these clusters were sampled to $L \ll L^*$. Figure 1 shows the quality of the data set and the evidence for velocity streaming within the cores of the giant ellipticals [see also 16]. Faber [11, 12] interpreted the existence of cores within these galaxies as evidence for multiple super massive black holes still remaining from the mergers of smaller systems and our kinematic data support that interpretation. Assuming that elliptical galaxies all form through major mergers we might expect that evidence of the super massive black holes within their progenitors could remain, especially for systems that have formed through dry mergers. In fact, we find that <u>all</u> the giant ellipticals ($L > L^*$) within the WFPS shows evidence for complex streaming while the vast majority of low luminosity systems ($L < L^*$) show smooth Gaussian velocity fields. We have developed a multicomponent fitting procedure for the line of sight velocity field with the goal of quantifying the number of quiescent super massive black holes within the giant galaxies. Similar high-resolution data acquired with 8-meter class telescopes and the ELTs would allow this phenomena to be characterized over a broad range of redshifts ($0.5 < z < 2$).

With the addition of photometric data, the FP for elliptical galaxies and its various projections [6,8] can be constructed. Figure 1 shows the FP for the four most extensively sampled clusters within the WFPS. Even a cursory look at the data suggests that the structural properties of the giant ellipticals ($L > L^*$) is quite different from the lower luminosity systems ($L < L^*$). The dashed lines in each panel are drawn at $L = L^*$ in order to provide a separation of these populations within each projection of the FP. In particular, the bottom two panels show a clear distinction between these two populations. The lower luminosity galaxies appear to constitute a dissipational sequence, suggestive of gaseous (wet) mergers, while the most luminous galaxies do not fall along a dissipational trend. This suggests that the location of a particular elliptical galaxy within the FP provides a measure of the relative role of wet vs. dry mergers averaged over its assembly history. This hypothesis is also consistent with the presence of complex velocity structure within the giants. To date the moderate- to high-z exploratory FP surveys have been limited to only the brightest galaxies [13, 14, 33, 35] and so a comparison with the WFPS data shown here is not possible. However, a directed survey to acquire similar spectroscopy from $0.3 < z < 2$, when combined with deep, high resolution imaging from HST and JWST, would allow the evolution of the FP over cosmic time to be characterized. The spectroscopic aspect of the survey would also allow the downsizing of star formation and the metallicity enrichment history of these systems to be characterized as well. This would be extremely interesting given that WISE imaging of high-z clusters [10, 34] suggests that a rapid downsizing of star formation is present within the $z \sim 1$ cluster populations and for their infalling populations as well.

Another means of quantifying the assembly history of elliptical galaxies is through the construction of the internal velocity dispersion distribution function (VDDF) [1, 25]. Figure 2 shows the VDDF for the four most deeply sampled clusters within the WFPS. The data are corrected for incompletion and fit with a modified Schechter function [24]. The resulting fit of the characteristic velocity dispersion (σ^*) provides another quantitative measure of the assembly history of a particular cluster or sample. For example, we [1] have found that the VDDF of the A2199 cluster, with its dominant cD galaxy has a σ^* that is significantly lower that that of the renaming clusters, which are indistinguishable from each other (95% significance). This provides direct evidence that the growth of the cD is a direct result of the major merger of $L \sim L^*$ gas-poor, systems, as these are absent from the cluster population. That is, the cD formation is through major mergers and not the result of a cooling flow and associated low-level star formation. A targeted, multi-telescope project aimed at moderate-z clusters would allow these various phenomena to be quantified in anticipation of the ELTs, which will then allow this characterization to be extended over the epoch of peak cosmic assembly ($z \sim 2$).

Specific Survey Requirements

The substantial investment being made in the ELTs requires that astronomers make every attempt to maximize the resulting science. This in turn will require the construction of large, statistically significant, foundational data sets over the next decade that establish the evolutionary trends present at low to moderate redshift in order to support the anticipated ELT data that will be acquired at the highest redshift. This should involve an extension of the WFPS to more fully sample the sub-L* populations in more nearby clusters with small telescopes. At intermediate redshifts the characterization of the FP, VDDF, and SMBH populations will require an extensive spectroscopic survey with 8-meter class telescopes such as Gemini. Tracking galaxy assembly over a broad range in redshift and environments will require an understanding of the progenitor bias. Specifically, we will need to be conscious of the fact that the progenitors of the elliptical population of nearby clusters will appear very different at high redshifts as they undergo assembly with the associated star formation and metal enrichment. Thus, we need to devise method for characterizing the formation/assembly state of a given cluster in order to track various processes as they evolve. One of the least biased approaches is to select intermediate- and high-z clusters on the basis of their x-ray characteristics and use models to account for evolution in order to compare “apples to apples.” In this way we can hope to ensure that both the foundational survey and the high-z surveys with the ELTs will be as fair and representative as possible. As an example of this possible bias, it is noted that there is considerable infall of gas-rich systems into intermediate redshift clusters [4,35] as well as evidence for star-forming systems with “proto-elliptical” morphologies [10,34]. This strongly suggests the need for similar surveys over a broad range of redshifts and environment if we are to understand and galaxy assembly, particularly as it relates to the role of the sub-L* systems.

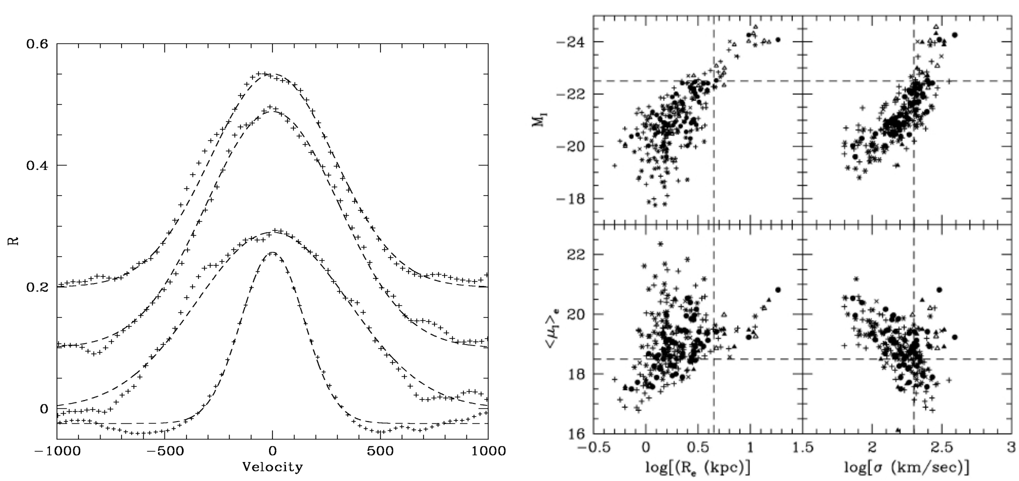

Figure 1: (left) Cross-correlation with a stellar template reveals the complex velocity structure for the giant ellipticals (L > L*) compared with the smaller systems (L < L*). (right) Various projections of the fundamental plane for four clusters in the WFPS. The dashed lines are drawn at L ~ L* to illustrate that the L > L* systems populate a distinct region within the FP (see lower right panel).

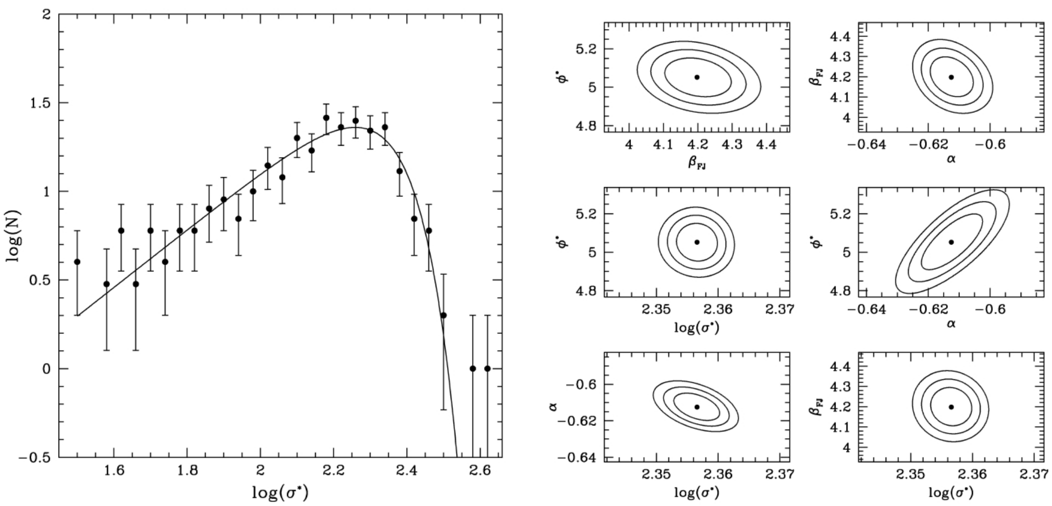

Figure 2: Parameterized fits of the VDDF provides a quantitative measure of the merger history of any particular elliptical galaxy cluster population.

In summary, the scientific potential of a dedicated, layer-cake, survey over the next decade to characterize the assembly of elliptical galaxies over modest redshift ($z < 1$) would stand alone and provide vital clues regarding the formation and evolution of elliptical galaxy populations. However, such a survey is also essential for providing the foundation upon which similar surveys over $1 < z < 2$ with the ELTs will be built. Only by designing a targeted survey that includes the low and moderate redshift universe, as well as the epoch of peak assembly, can we possibly fully understand the complexities of galaxy formation. The potential of the various projections of the structural scaling relations (i.e., the FP) in quantifying this precess is huge and has the potential to transform our understanding of the assembly history of elliptical galaxies.

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