Proposed Plan of Research

Tracing Galaxy Assembly: Tadpole Galaxies in the Hubble Ultra Deep Field

1-2. Research Plan and Study Objectives

As understanding of our universe has vastly increased over the years, a crucial problem remains largely unsolved—that of galaxy evolution. In the nearby universe we observe galaxies that are neatly classified in the familiar Hubble types, yet as we look into the higher redshift universe—particularly $z > 2$—we observe a much more peculiar universe filled with irregularly shaped galaxies that look nothing like the ones we see nearby. In addition, there is a definite gap in our knowledge of supermassive black hole formation. WMAP results suggest that massive Population III stars existed at z~20 with masses ~300 M, which likely exploded as pair-production supernovae, leaving behind black holes with masses ~150 M (Madau & Rees 2001). Looking at nearby galaxies (z~0), we observe supermassive black holes in their centers with masses of ~10^9 M (Kormendy & Richstone 1995; Kormendy & Gebhardt 2001). It is crucial to understand how this transition from ~150 M black holes at z~20 to ~10^9 at z~0 occurred. One popular theory is that the process by which this transition occurs is through hierarchical merging, though much remains to be studied regarding the specifics of these ideas.

The release of the Hubble Ultra Deep Field in March 2004 was eagerly anticipated by those that study galaxy evolution and morphology. It has motivated many new projects, many exploiting the unprecedented depth to which this field reaches. One particular phenomenon evident in the UDF is the abundance of galaxies that appear to be dynamically unrelaxed. These galaxies present morphologies characterized by a bright unresolved knot, plus an extended, dimmer "tail" to one side (see Figure 1), reminiscent of tadpoles. I have performed a preliminary study on these "tadpole galaxies" which has provided some interesting and surprising results, but has raised many new questions. The abundance alone of these objects suggests that they are dynamically a separate class from the familiar Hubble types, and thus should be studied in more detail. In particular, their morphologies suggest that they are merging systems, and thus the tadpole galaxies allow us to view a crucial time in galaxy evolution—the very process by which small, irregular galaxies build up into large, dynamically relaxed ones. I will perform several specific tests on these tadpole galaxies to confirm that they are indeed merging systems, as well as collect a larger sample of tadpoles in other existing deep data (i.e. GOODS HST fields) to improve statistics. I will measure the masses of the tadpoles (as described below) in order to detect the buildup of mass over redshift—a clear indication that merging events are occurring. I will also obtain spectra for the brightest tadpoles to further investigate the details of their dynamics and star formation.

The goals of this project are an excellent match to the goals & objectives of the NASA. Further investigation of the tadpole galaxies will provide essential insight into the scheme of galaxy evolution. ***In particular, this project will specifically address the Space Science Enterprise's Goal (1) to "Chart the evolution of the universe, from origins to destiny, and understand its galaxies..." and specifically the Enterprise's Objective to "Learn how galaxies...form, interact, and evolve."(Science Objective 3, Table I)*** This project is a specific study of the *earliest observable states* of galaxies. The project also, by its very nature, studies how galaxies *interact*; tadpole galaxies appear to be interacting systems. This process of interaction—galaxy merging events—is the primary process by which galaxy *evolution* occurs.

The Hubble Ultra Deep Field (Beckwith et al. 2005) is the deepest look at our universe to date. It provides a means to study galaxy morphology and evolution in detail to very faint flux levels. Motivated by the abundance of tadpole-shaped galaxies, I have written a program to systematically select the tadpole galaxies. Source extraction was performed using the SExtractor (SE) package (Bertin & Arnouts 1996). Two source catalogs were made, one that was highly deblended (such that crowded pointlike objects are separated into individual sources)—this catalog contained the potential tadpoles' "knots"; and one that had a low-deblending value set (crowded pointlike objects are counted largely as one source)—this catalog contained the tadpole's "tails". From the SExtractor-measured axis ratios, ellipticity cuts were made such that knots were rounded and tails were flattened. Nearby knot-tail features were matched on the image, and other selection criteria were imposed to narrow down the catalog of tadpole candidates (Straughn et al. 2005).

The UDF data is also unique in that it was obtained over a period of approximately four months and so variable objects can be searched for. Cohen et al. (2005) found 1% of objects (45 objects total) to AB < 28 to be variable; they conclude that these sources are likely AGN due to location within the host galaxies and the timescales on which they are variable (0.1-5.5 weeks in the rest-frame). The variability study is a partner study to the preliminary tadpole study, and the current proposed project.

The following are the main results that came from this preliminary study—results which demand further investigation. The final sample contained 164 tadpole galaxies to a magnitude limit of AB=28 mag in the *i*-band (F775W), which is ~6% of all field galaxies to this magnitude limit. We find that the photometric redshift distribution of the *tadpoles* follows that of the field galaxies (Figures 2 & 3). This is a surprising result; if indeed tadpole galaxies are dynamically young, then this indicates that galaxy assembly kept up with the reservoir of available field galaxies as a function of cosmic epoch. The redshift distribution of the *variable* objects also follows that of the field population; the surprising result is that the tadpole galaxy sample has almost no overlap with the sample of variable objects in the UDF. Therefore, *the tadpole galaxies' morphologies combined with the lack of overlap between the tadpole sample and the sample of objects found to be variable support the idea that these galaxies are in the process of a merger event, i.e. at a stage that precedes the "turn-on" of their AGN and onset of variability*. Recent hydrodynamical models by Springel, Di Matteo & Hernquist (2004) suggest that the supermassive black hole accretion rate peaks well *after* the major merger (as traced by tadpoles) started. In particular, their models *look* like tadpoles before the AGN activity begins. We believe that we may be seeing this process in the UDF; however, much more testing is required to confirm this hypothesis. I will perform these tests, as well as further investigation into the details of the tadpole galaxies as outlined in the following section.

Summary of Science Goals:

1. Confirm the hypothesis that tadpole galaxies are indeed merging systems
2. Obtain and analyze a larger sample of tadpole galaxies to improve statistics
3. Quantify morphological characteristics of tadpoles
4. Investigate in detail the link between the observed tadpole/AGN sample and hydro-dynamical models that predict the buildup of supermassive black holes via major mergers

3-4. Methodology and Key Elements

1. Confirm the hypothesis that tadpole galaxies are indeed merging systems

1a. I will perform a detailed color analysis in order to measure the star formation rate and stellar masses. For many years enhanced star formation has been a known indication of merging activity (Larson & Tinsley 1978). I will use the Bruzual & Charlot (2003) stellar population synthesis models to measure star formation rates and stellar masses based on the available *BVi'z'* and *JH* photometry. Similar work has been performed previously by Papovich, Dickinson, & Ferguson (2001) in the HDF North. By measuring an enhanced star formation rate, I can confirm that these tadpole galaxies are major mergers.

1b. I will propose to obtain spectra for the brightest tadpoles with z <1 from Gemini. Superb spectra could reveal important velocity information and thus confirm and expound upon the dynamical properties of these galaxies and give line strengths that will provide information about the star formation rates.

2. Obtain a larger sample of tadpole galaxies to improve statistics

2a. I will analyze the GOODS North and South fields using the same methods the UDF was analyzed with, using my tadpole-selector code written in IDL. This should produce ~1000 more tadpoles.

2b. Perform the tadpole search in the UDF *z*-band data. This step will not result in a larger *sample* of tadpole galaxies, but should be done for completeness. In particular, there are several noticeably red tadpole-shaped galaxies in the composite image of the UDF; these are possibly high-redshift *i*-band dropouts and thus have potential for interesting results themselves.

2c. A Hubble Space Telescope Cycle 14 Proposal (Rogier A. Windhorst, PI) has been submitted to obtain new images in the CDF-S fields. If approved, this will provide a larger tadpole sample, as well as improve the photometric redshift determination.

3. Quantify morphological characteristics of tadpoles/investigate clustering tendencies

I will use the "CAS" parameters as defined by Conselice et al. (Conselice, Bershady & Jangren 2000) to compare their merger definition to my tadpole sample, and help delineate the suspected new galaxy population.

4. Investigate in detail the link between the observed tadpole/AGN sample and hydro- dynamical models that predict the buildup of supermassive black holes via major mergers

I will further investigate the lack of variability in the knots of the tadpoles. We need to identify *why* most high-z early-stage mergers—as traced by tadpoles—do not show AGN activity. In particular, we need to find out if the AGN is inactive, hidden, or absent. Detailed comparison to the hydrodynamical models mentioned above will quantify the delay between the early stages of galaxy mergers and the triggering of their AGN and onset of variability.

5-6. Timetable and Milestones

05/2005 to 10/2005	Perform additional tadpole searches in other fields
08/2005 to 12/2005	Measure star formation rates and stellar masses of tadpoles
12/2005 to 2/2006	Obtain & analyze spectra for faintest tadpoles
02/2006 to 04/2006	Measure/quantify morphological parameters
02/2006 to 05/2007	Detailed comparison to hydrodynamical models
02/2006 to 05/2007	Analysis of new HST data (if applicable)
05/2008	Complete analysis and finalize dissertation material

References

Beckwith, S., et al. 2005, AJ, in preparation
Bertin, E. & Arnouts, S. 1996, A&AS, 117, 393
Bruzual, G. & Charlot, S. 2003, MNRAS, 344, 1000
Cohen, S.H. et al. 2005, Nature, submitted
Conselice, Bershady & Jangren 2000, ApJ 529, 886
Conselice, C. et al. 2003, AJ, 126, 1183
Kormendy, J. & Richstone, D. 1995, ARA&A, 33, 581
Kormendy, J. & Gebhardt, K 2001, AIP Conf. Proc. 586, 363
Larson, R.B. & Tinsley, B.M. 1978, ApJ, 219,46
Madau, P. & Rees, M. 2001, ApJ, 551, L27
Papovich, C., Dickinson, M., & Ferguson, H.C. 2001, ApJ, 559, 620
Springel, V., Di Matteo, T., & Hernquist, L. 2004, astro-ph/0411108

Figures

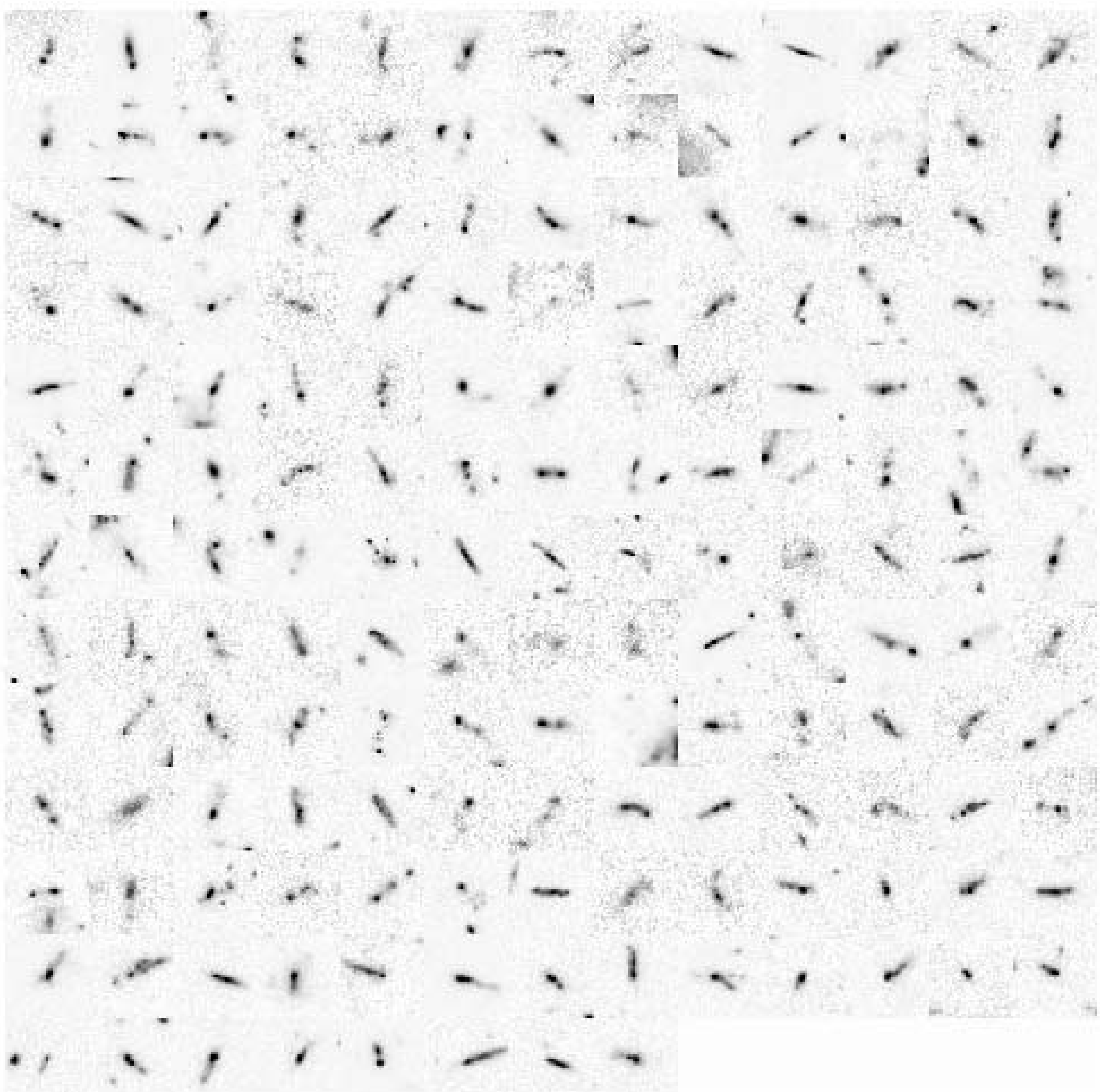
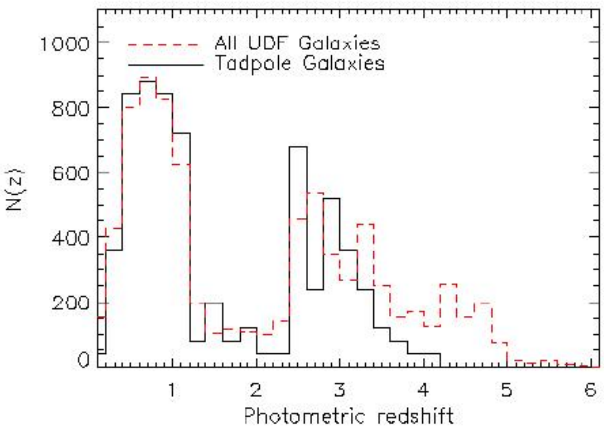


Figure 1. Final sample of 164 selected tadpole galaxies.



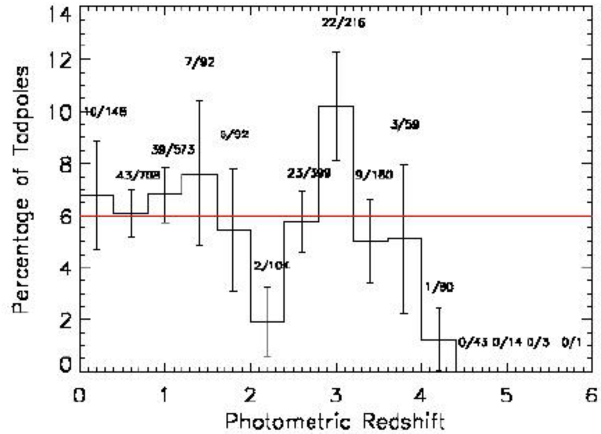


Figure 2. Photometric redshift distribution. Tadpoles are multiplied by a factor of 16 for for comparison to all field galaxies.

Figure 3. Percentage of galaxies that are tadpoles as a function of photometric redshift. Roughly 6% of galaxies are tadpoles at all redshifts.