QUALIFYING EXAM 2004: RESEARCH REPORT

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1. SUMMARY OF RESEARCH

Galaxies are the building blocks of the observable universe, and understanding their formation and evolution is fundamental to our understanding of the physical processes which govern the development of light and dark structure in the universe. The high-redshift environment offers the unique possibility of directly observing the formation of galaxies from proto-galactic fragments in the early universe: With this possibility in mind, under the guidance of my advisor Chuck Steidel I have begun a study of the irregular morphologies of galaxies in the Hubble Deep Field North (HDFN) in the redshift range $z = 2 - 3$ (corresponding to times when the universe was roughly $15\% - 25\%$ of its current age). I have developed an interactive online database containing 1300 high redshift galaxy candidates in the HDFN region which have been selected using variants of the UGR photometric technique (see, e.g., Steidel & Hamilton 1993; Adelberger et al. 2004) and consolidating photometric and morphological data obtained using the Hubble Space Telescope Advanced Camera for Surveys (ACS) and spectroscopic data collected over the past few years by Steidel and colleagues. With the aid of a Caltech undergraduate SURF student, I have helped design and implement statistical tests to search this database for possible correlations between galaxy morphologies and spectrophotometric features, since such associations could indicate the dominant physical mechanisms (e.g. star formation, dust obscuration, galaxy mergers, etc.) in these sources. While our analyses have not yet yielded many solid associations, preliminary results suggest the possibility of statistical associations between the strength of key spectral lines and the degree of morphological irregularity of the source.

Under the hierarchical structure formation paradigm (e.g., Searle & Zinn 1978), the process of galaxy assembly should be continuing today in the local universe, and the experience gained from developing an understanding of the ongoing galaxy assembly process in the Milky Way (for which a relative wealth of information is available) can contribute substantially to efforts to understand galaxy formation in the early universe. A growing body of evidence suggests that the Milky Way Galaxy is still accreting dwarf companions from its halo, as evidenced by visible tidal streams of stellar debris from satellites currently disrupting in the Galactic potential (e.g., Ibata et al. 1997; Leon, Meylan, & Combes 2000). Perhaps the most compelling example of ongoing tidal disruption is the Sagittarius (Sgr) dSph galaxy, which has recently been shown by Majewski et al. (2003) to have tidal debris arms wrapping over 360° around the Galaxy. In collaboration with Steve Majewski (Virginia) and Kathryn Johnston (Wesleyan), I have developed simulations of the tidal disruption of the Sgr dwarf based on the all-sky view presented by the Two Micron All-Sky Survey (2MASS) catalog (Majewski et al. 2003), effectively mapping out the shape and strength of the Galactic potential with unprecedented accuracy and determining that while the present day dark halo is probably oblate with an axial ratio $q \sim 0.9$ some evolution in this potential has likely occurred during the past few Gyr. Our results have recently been submitted to the Astrophysical Journal for publication (Johnston, Law, & Majewski 2004, and Law, Johnston, & Majewski 2004).

2. HIGH-REDSHIFT GALAXIES

Since it is not generally possible to measure the detailed velocity substructure of high-redshift galaxies, a popular alternative has been to examine morphological characterizations and explore what these rest-frame UV morphologies, in conjuction with spectrophotometric features, can tell us about the structure of these sources. In order to assess the extent of the presently available data and its usefulness for exploring galaxy structure, I have consolidated these data into an online database of 1300 photometrically selected high-redshift galaxy candidates in the HDFN. This database contains such information as U, G, R, J and K magnitudes, morphological parameters calculated via prescriptions outlined in part by Erb et al. (2004), spectroscopically determined redshifts, Lyα, Hα, and metal line strengths, and velocity dispersion information for those sources for which high-resolution spectroscopic data is available (Erb et al. 2004). This database has been designed with an eye to its usefulness as a quick-reference source for HDFN galaxies in future investigations, but is primarily intended to be a robust, queryable database for use in a statistical cross-correlation analysis of galactic parameters which I have overseen the design and implementation of over the past few months.

With the aid of a Caltech undergraduate SURF student working under my supervision, jpeg images of 300+ spectroscopically confirmed high-redshift sources in the HDFN have been added to the internet database for all four ACS filters (B, V, I, Z) as well as composite RGB color images and B-Z color difference maps (see Fig. 1). Similar to the findings of Abraham et al. (1999), Figure 1 demonstrates that these composite color maps can readily illustrate photometric differences between lumps within a given source — possibly suggesting an ongoing galaxy merger, differential dust obscuration, and/or non-uniform star formation rates in the visible knots. Such color map information could be of use in automatically identifying those sources which are candidates for further spectroscopic study and which may possess unusual kinematic substructure.

In addition to helping the SURF student under my supervision learn the standard astronomical image processing tools necessary for producing the ACS images,

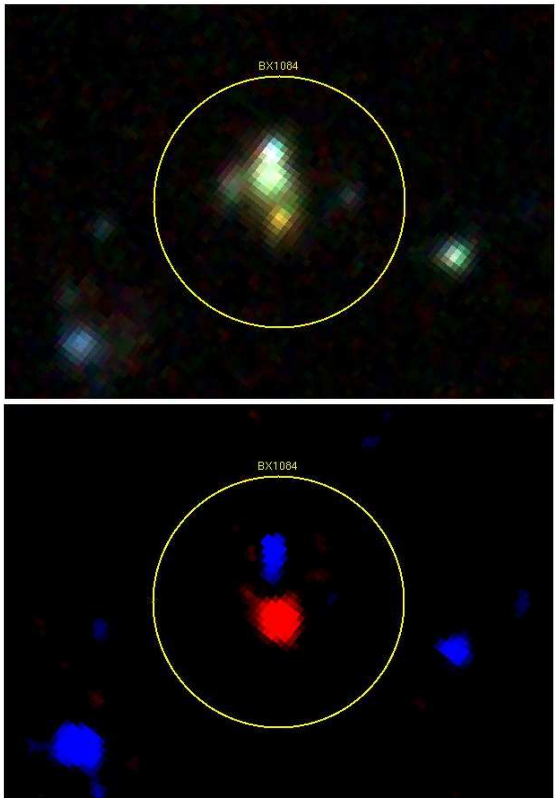

FIG. 1.— *Top panel*: RGB color composite image of the HDFN source BX1084 based on HST ACS data in B, V, I and Z bands. *Lower panel*: $B - Z$ flux difference color map of the same source. The yellow circle is 2” in diameter.

I have also guided him through the process of learning practical C++ programming for data analysis and have helped him design and implement non-parametric statistical tests for an all-way correlation analysis between each of the over 40 data variables in the galaxy database. If strong correlations are found, these correlations could help discriminate between the possible physical mechanisms governing the behavior of the variables, aiding our understanding of the dominant physical mechanisms at work in the system.

Although final revisions of the statistical analysis code have yet to be made, preliminary results have already recovered some correlations expected on the basis of previous work. Figure 2 shows the increase in source multiplicity (i.e. “blobbiness”, $KAm5$) and decrease in apparent angular size ($KAnhsb$) with redshift, as expected on the basis of observational work by (e.g.) Shapley et al. (2001), van den Bergh (2001), and Conselice et al. (2004). These trends indicate that we increasingly observe galaxies in the process of forming at progressively higher redshifts, although the interpretation of these data is complicated since the observed morphologies probe the source rest-frame UV light distribution which tends to be a lumpy tracer of recent star-forming regions (see, e.g., Kuchinski et al. 2001, for a discussion of this bandshifting effect). Early results also suggest the possible existence of a statistically significant correlation between the strength of the Lyα absorption line and the multiplicity of the system (Fig. 3). Such a correlation could imply that systems with higher multiplicity are either dustier or have different star formation rates than more concentrated systems, as explored for the case of Hα equivalent widths by van Dokkum et al. (2004).

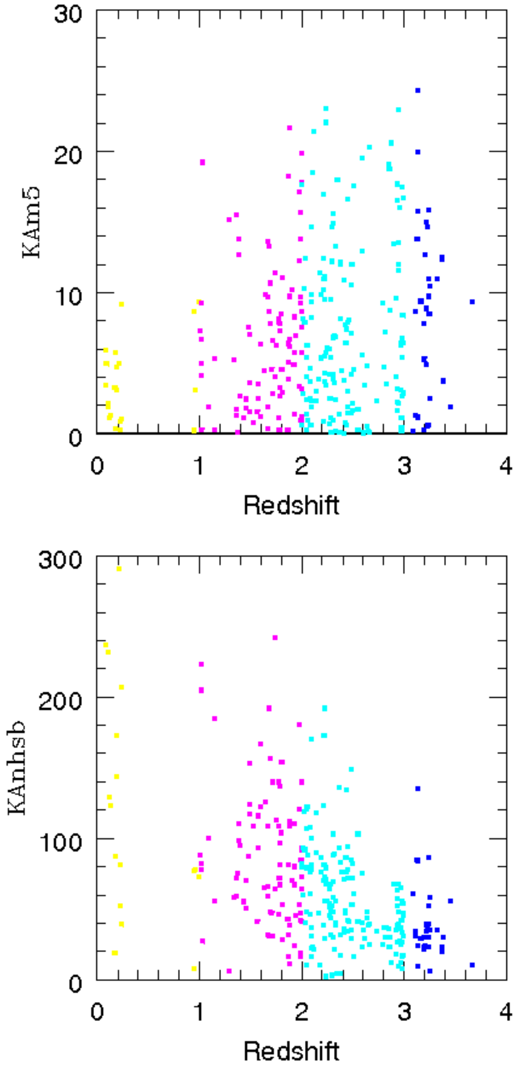

FIG. 2.— *Top panel*: Increasing trend of galaxy multiplicity $KAm5$ with redshift. *Lower panel*: Decreasing trend of apparent galaxy size $KAnhsb$ with redshift.

In addition to developing the galaxy database and statistical correlation analyses, I have also invested considerable time in learning the observational techniques required to pursue a study of high-redshift galaxy structure over the next few years. I have spent five nights at the duPont telescope at Las Campanas Observatory learning the UGR imaging technique (Steidel & Hamilton 1993; Adelberger et al. 2004) by which the high-redshift galaxy candidate sample is obtained, and have also spent eight nights at the Keck telescopes gaining valuable familiarity with the LRIS and NIRSPEC spectrographs and the data products thereof (see, e.g., Pettini et al. 2000). Such experience will be useful in formulating an observing plan with the aid of my advisor to investigate high-redshift galaxy structure over the next few years.

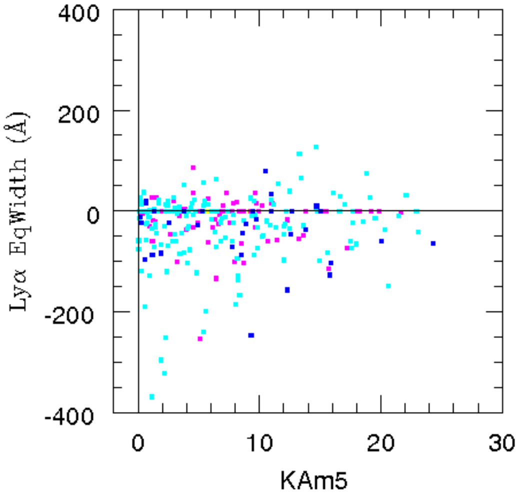

FIG. 3.— Rest-frame Lyα equivalent width versus source multiplicity parameter $KAm5$. Colors indicate source redshift as illustrated in Figure 2.

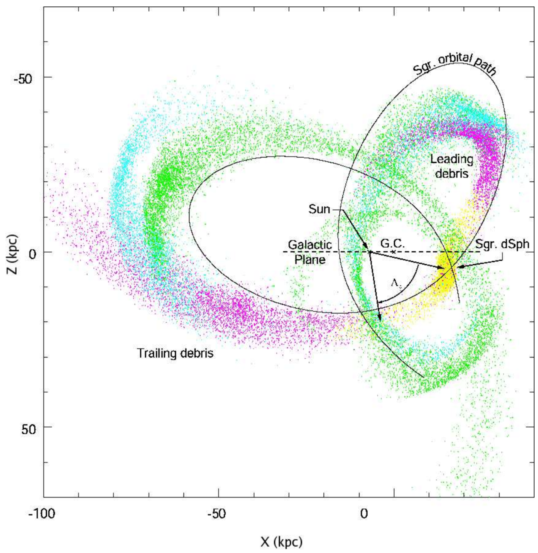

FIG. 4.— Typical appearance of an N-body tidal debris model of the Sgr dwarf (colored points) in the Galactic Cartesian coordinate system. Each color corresponds to debris lost during a single radial orbit, and the solid line is the projected orbit of the Sgr dwarf core. Bold arrows define a longitudinal coordinate system $\Lambda_\odot$. [From Law, Johnston, & Majewski 2004]

3. GALACTIC STRUCTURE

Substantial studies have been undertaken to determine the dark matter distribution in galaxies in the local universe (see Merrifield 2002 for a summary), and in clusters of galaxies at intermediate redshifts (e.g., Kneib et al. 2003). It is unfortunate however that while we are beginning to determine the shapes and assembly histories of external galaxies, we are still uncertain of the shape and history of our own Milky Way Galaxy. Indeed, a comprehensive knowledge of how hierarchical formation processes are continuing today at $z = 0$ is likely to give insight into formation processes at work in the early universe.

A major advantage of studying the Milky Way is that there exist visible dynamical tracers of the Galactic mass distribution in the form of stellar streams: Dwarf satellites on eccentric orbits about the Milky Way experience substantial tidal forces which cause stars to become unbound from their parent satellites into coherent tidal streams (e.g., Tremaine 1993; Johnston, Spergel, & Hernquist 1995) which can be used to trace the orbital history of the satellite. Using N-body simulations, the shape of the Galactic potential can hence be determined by requiring model satellites to reproduce the observed trends of satellite debris.

The Sagittarius (Sgr) dSph presents one of the most compelling examples of this tidal destruction; its tidal tails have recently been traced over 360 deg around the sky using M giants stars selected from the 2MASS survey (Majewski et al. 2003). Previously, studies (e.g., Ibata et al. 1997; Johnston, Spergel, & Hernquist 1995) have sought to model the Sgr - Milky Way interaction using only the detections of probable Sgr debris from small, pencil-beam surveys. Taking advantage of the substantial improvement in our knowledge of the Sgr system provided by the M giant data, in collaboration with Steve Majewski and Kathryn Johnston I have developed new models of the tidal destruction of the Sgr dwarf (Law, Johnston, and Majewski 2004), considerably improving previous constraints on the size and shape of the Milky Way potential, and on the mass and orbital history of the Sgr dwarf. Figure 4 shows the results of one such N-body model and illustrates the large scale on which the Sgr tidal streams have been observed to wrap around the Galaxy. We have demonstrated that in order to reproduce the observed M giant distribution and radial velocity trends (Majewski et al. 2004) of Sgr tidal debris the mass of the Milky Way within 50 kpc must be 4 - 6 $\times 10^{11} M_\odot$, that the Galactic halo potential must be oblate with an axial flattening of $q = 0.9$ in order to match the observed precession of the tidal debris plane (Johnston, Law, & Majewski 2004; see Fig. 5), and that some evolution in the Galactic potential and/or the orbit of the Sgr dwarf must have occurred in the past few Gyr in order to account for the observed radial velocities of tidal debris unbound from the satellite roughly 2 Gyr ago. These models predict the presence of Sgr tidal debris in the solar neighborhood, raising the possibility that some nearby stars could have been born in an environment rather different from the local Galactic disk (a prospect which could affect our understanding of local stellar populations), and that the Sun may be bathing in a stream of tidally stripped *dark matter* particles, affecting the potential interpretation of results from WIMP detection searches (Freese et al. 2004). In addition, we have demonstrated that the observed dispersion of the tidal stream requires the presently bound mass of Sgr to be in the range 2-5 $\times 10^{8} M_\odot$, constraining the mass to light ratio to be $M/L = 14$ - 36 (solar units), substantially improving the previous spread of estimates for the mass-to-light ratio which ranged up to $M/L \sim 100$ (Ibata et al. 1997).

4. FUTURE WORK

A great deal of uncertainty remains in the interpretation of the apparent substructure of high-redshift galax-

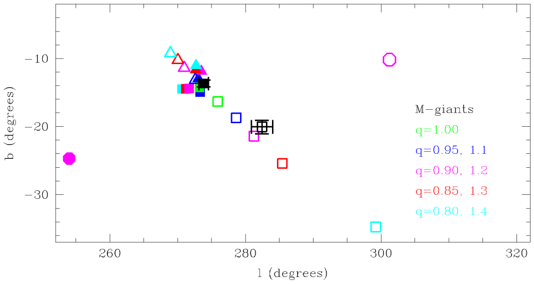

FIG. 5.— The positions of apparent orbital poles in Galactic coordinates for the M giants and simulated debris calculated using a plane-fitting technique. Open/filled symbols represent the poles of leading/trailing tidal debris, squares/triangles are for oblate/prolate potentials. Circles represent orbital poles for the $q = 0.90$ simulation calculated from older, more greatly precessed tidal debris. [From Johnston, Law, & Majewski 2004]

ies, even in those cases for which some velocity dispersion information is available (e.g., Erb et al. 2004). Ideally, we would like to be able to examine the internal kinematics of these high-redshift galaxies in detail to investigate to what extent dynamical order underlies the morphological confusion. This exciting prospect could become a reality in the near future using the new OSIRIS spectrograph operating on the Keck telescope with the aid of a laser-projected guide star and adaptive optics system. The OSIRIS integral-field IR spectrograph, currently in the final phases of testing at UCLA, aims to achieve simultaneous spatially resolved spectroscopy of $\sim 10^3$ elements within a field of size 10 arcsec^2; a spatial resolution which could reveal tantalizing substructure in high-redshift sources. It is presently unknown whether the sensitivity or spectral resolution of OSIRIS will be sufficient to permit such a study however, and I therefore intend to perform a design study during Fall 2004 to assess the feasibility of using OSIRIS for such work.

In the meantime, the recently launched SPITZER space telescope can provide important rest-frame IR photometric data to complement the rest-frame UV data from HST. While the SPITZER images unfortunately do not have the spatial resolution required to probe IR morphologies, useful infomation can nonetheless be gleaned from measurements of the integrated brightness of the sources, which can then be used for statistical analyses in conjunction with the data already in the galaxy database.

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