Lyman Alpha Emitting Galaxies at High Redshift: Direct Detection of Young Galaxies in a Young Universe

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Steven Arthur Dawson

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B.A. (University of California at Irvine) 1998
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Abstract

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Steven Arthur Dawson
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An early result of galaxy formation theory was the prediction that the copious ionizing radiation produced in nascent galaxies undergoing their first starbursts should in turn produce a strong Lyα emission line. We report on our efforts to detect and characterize primeval galaxies by searching for this expected Lyα signature with two observational techniques: serendipitous slit spectroscopy, and narrowband imaging selection. In Part I, we describe our serendipitous slit spectroscopy survey of the Hubble Deep Field and its environs, which resulted in a catalog of 74 spectroscopic redshifts spanning $0.10 < z < 5.77$, including a galaxy cluster at $z = 0.85$ and five galaxies at $z > 5$. Follow–up observations at higher resolution resulted in the additional serendipitous detection of a strong Lyα–emitting galaxy at $z = 5.190$ (ES1). At the time of its discovery, ES1 was one of only nine known galaxies at $z > 5$, and was the sixth most distant known galaxy. The unprecedented spectral purity of the observation offers evidence for a galaxy–scale outflow with a velocity of $v > 300$ km s^{-1}, consistent with wind speeds observed in powerful local starbursts (typically 10^2 to 10^3 km s^{-1}), and with simulations of the late–stage evolution of Lyα emission in star–forming systems. Our final serendipitous detection is the remarkable source CXOHDFN J123635.6+621424, which is both the highest redshift known spiral galaxy, and a rare example of a high redshift, hard X–ray–emitting Type II AGN. Significantly, all of these results were acquired with no direct allocation of telescope time.

In Part II, we report on our implementation of narrowband imaging selection, with which we traded redshift coverage for survey volume, focusing on the systematic study of galaxies at a particular epoch in favor of chasing that rare, most–distant object. This effort resulted in a catalog of 76 $z \approx 4.5$ Lyα–emitting galaxies spectroscopically–confirmed in campaigns of Keck/LRIS and Keck/DEIMOS follow–up observations to candidates selected in the Large Area Lyman Alpha (LALA) survey. We find that a significant fraction of the confirmed Lyα lines have rest–frame equivalent widths ($W_\lambda^{\rm rest}$) which exceed the maximum predicted for normal stellar populations: 12% – 27% of the galaxies in the sample show $W_\lambda^{\rm rest} > 240$ Å (90% confidence), and 17% – 31% show $W_\lambda^{\rm rest} > 190$ Å (93% confidence). Furthermore, the narrow velocity widths ($\Delta v < 500$ km s^{-1}) together with a lack of high–ionization state emission lines support the conclusion that the Lyα emission in these sources derives from star formation, not from AGN activity. However, the nondetection of He II $\lambda 1640$ in both individual and composite spectra (to a 2σ [3σ] upper limit of 13% [20%] of the flux in the Lyα line) dictates that though these galaxies are young, they show no evidence of being truly primitive, Population III objects. We also find that the Lyα lines in this sample systematically disfavor combinations of low velocity width (< 150 km s^{-1}) and high luminosity ($> 5 \times 10^{42}$ erg s^{-1}), suggesting that more than dust content alone, it is the velocity structure of a galaxy that determines the detectability of Lyα in emission. Finally, we construct a luminosity function of $z \approx 4.5$ Lyα emission lines for comparison to a set of Lyα luminosity functions spanning $3.1 < z < 6.6$. We conclude that if there is evolution in the Lyα luminosity function over these epochs, its significance is below the statistical uncertainty of these data. This result supports the conclusion from several smaller samples of high–redshift Lyα–emitters that the intergalactic medium remains largely reionized from the local universe out to $z \approx 6.5$. However, it is somewhat at odds with the pronounced drop in the cosmic star formation rate density recently measured between $z \sim 3$ and $z \sim 6$ in Lyman–break galaxies, and therefore potentially sheds light on the relationship between the two populations.

Professor Hyron Spinrad
Dissertation Committee Chair

to the current Dr. Dawson, the future Dr. Dawson,
and the Mrs. Dawson who made it all possible

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And now, let's get astrophysical.

Chapter 1

Introduction: The Failed Search for Primeval Galaxies

Almost four decades ago, Partridge & Peebles (1967) predicted that galaxies undergoing their first throes of star formation should be strong emitters in the Lyα emission line. Coupled with this prediction was the expectation that the detection of such young galaxies would offer insight into theories of galaxy formation and evolution, would provide *in situ* information on star formation under conditions not found locally, and would likely lead to the detection of objects at high redshift, providing insight into physics at early epochs. Motivated by these considerations, observers spent the next 30 years searching for the highly redshifted Lyα emission which would signify the expected widespread population of galaxies undergoing their first starbursts. Though a handful of Lyα–emitters were detected in the vicinity of objects already known to be at high redshift (e.g. Djorgovski et al. 1985, 1987; Hu & McMahon 1996; Hu et al. 1996; Petitjean et al. 1996), these results were dismissed as a consequence of the possibly anomolous environments around the target objects (Cowie & Hu 1998). Meanwhile, the results of all blank–field surveys were identically disheartening: no emission–line primeval galaxies were found.

The main issue hampering the unsuccessful searches was a general failure to achieve sufficient limiting flux sensitivities. By the mid–1990s, searches for primeval Lyα had achieved flux levels and survey volumes which, according to simple models, ought to have detected thousands of objects (Pritchet 1994), and yet inexplicably, the population remained elusive. The situation was finally remedied by the commissioning of 10–meter class telescopes. By exploiting the substantial gain in depth afforded by these unprecedented apertures (especially when coupled with the growing availability of large–format mosaic CCDs well–suited for wide–field imaging and spectroscopic multiplexing), emission–line searches ultimately did uncover a substantial population of high–redshift Lyα–emitters, albeit with Lyα fluxes nearly two orders of magnitude fainter than originally predicted.

That said, the search techniques used in past decades are fundamentally the same as the techniques used to great success today. In this thesis, we present results from our efforts to detect and characterize primeval galaxies by their signature high–redshift Lyα emission lines utilizing two observational techniques: serendipitous slit spectroscopy and narrowband imaging. By pushing these techniques to their utmost limits, we probe the Lyα–emitting galaxy population out to redshifts as high as $z \approx 6.5$, bordering and perhaps breaching the very epoch of reionization (e.g. Malhotra & Rhoads 2004; Stern et al. 2005). In the currently favored Λ–cosmology[1], with $\Omega_{\rm M} = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1}, galaxies at this epoch reside in a universe which is just 800 million years old, a mere 6% of its current age. We now motivate this effort by situating it within the field of observational cosmology as a whole (§ 1.1) and by comparing competitive techniques for detecting high–redshift objects (§ 1.2 and § 1.3). We conclude with an overview of the thesis to follow (§ 1.4).

1.1 History: Breaching the Realm of the Nebulae

Modern observational cosmology, with its modest aim of "understanding the entire universe and all its contents" (Peacock 1999), finds its foundation in the interplay between a handful of revelations made during the first few decades of the 20th century. Chief among these discoveries was the confirmation that the spiral nebulae are indeed "island universes" unto themselves (Opik 1922; Hubble 1925, 1926), with masses comparable to that of our own galaxy. Subsequent measurements of the distances to the nebulae, now known to be extra–galactic, yielded the surprising result of Hubble's Law, that the recession speed of galaxies as indicated by their redshifts is linearly related to their distances (Hubble 1929).

The rapid acceptance of this startling observational result was no doubt due in part to the fact that the theoretical underpinnings for an expanding universe had recently come into place. Einstein's General Theory of Relativity (Einstein 1915a,b,c), coupled with the assumption of a homogeneous, isotropic universe, required a world model which (in

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[1] Unless otherwise specified, we use this cosmology throughout.

the absence of a cosmological constant) either expands or contracts. Friedmann (1922) gave the solution for the expanding case, which was rediscovered by Lemaitre (1927) and subsequently connected to the burgeoning phenomenon of redshifted galaxies. As a result, in the synergy between the new body of cosmology theory and the growing catalog of extra–galactic observations was born the notion that the universe expanded from an initial hot, dense state in which the radiation density dominates the matter density — an idea which was alternately welcomed as a harbinger of new physics (Lemaitre 1931), and vilified for its philosophical repugnance (Eddington 1931).

On either interpretation, this standard cosmological model leaves open the question of how the universe evolved from its smooth initial state to its current state, in which the typical distance between the highly discrete groups of matter known as galaxies is on the order of megaparsecs, while the typical sizes of the galaxies themselves are on the order of kiloparsecs. In fact, that galaxies exist at all as such remarkable departures from homogeneity remains one of the most fundamentally striking cosmological mysteries. Under the current Cold Dark Matter paradigm, structure forms from the growth of very tiny adiabatic density perturbations in the primordial dark matter distribution (e.g. Eggen et al. 1962; Sandage et al. 1970; Peebles 1971; Press & Schechter 1974). The density perturbations grow and collapse under gravitational instability, and the resulting overdensities cause gas to accumulate, cool, and form stars (e.g. White & Rees 1978). Thereafter structure grows hierarchically, with proto–galactic clumps forming at comparatively high redshift ($z \gtrsim 10$), and then merging into larger galaxies and finally clusters (e.g. Baron & White 1987; Baugh et al. 1998).

Observationally, the standard cosmological model has the simple consequence that — because the speed of light is finite — light detected from distant galaxies was emitted when the universe was significantly younger. Thus, to identify and characterize high–redshift galaxies is to look back in time, to observe the ancestors of the present–day galaxies in the very midst of their formation and evolution. The search for primeval galaxies therefore provides direct access to the simplest and most fundamental lines of physical inquiry: how will the world end, how did it begin, and what happened in between.