

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

by

Steven Arthur Dawson

ISBN: 1-58112-294-2

DISSERTATION.COM



Boca Raton, Florida
USA • 2005

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

Copyright © 2005 Steven Arthur Dawson
All rights reserved.

Dissertation.com
Boca Raton, Florida
USA • 2005

ISBN: 1-58112-294-2

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

by

Steven Arthur Dawson

B.A. (University of California at Irvine) 1998
B.S. (University of California at Irvine) 1998
M.A. (University of California at Berkeley) 2000

A dissertation submitted in partial satisfaction of the
requirements for the degree of
Doctor of Philosophy

in

Astrophysics

in the

GRADUATE DIVISION
of the
UNIVERSITY OF CALIFORNIA, BERKELEY

Committee in charge:
Professor Hyron Spinrad, Chair
Professor Chung-Pei Ma
Professor William L. Holzapfel

Fall 2005

The dissertation of Steven Arthur Dawson is approved:

Chair

Date

Date

Date

University of California, Berkeley

Fall 2005

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

Copyright 2005

by

Steven Arthur Dawson

Abstract

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

by

Steven Arthur Dawson

Doctor of Philosophy in Astrophysics

University of California, Berkeley

Professor Hyron Spinrad, Chair

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 Ly α emission line. We report on our efforts to detect and characterize primeval galaxies by searching for this expected Ly α 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 Ly α -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 $v > 300 \text{ km s}^{-1}$, 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 Ly α 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 $z \approx 4.5$ Ly α -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 Ly α lines have rest-frame equivalent widths ($W_{\lambda}^{\text{rest}}$) which exceed the maximum predicted for normal stellar populations: 12% – 27% of the galaxies in the sample show $W_{\lambda}^{\text{rest}} > 240 \text{ \AA}$ (90% confidence), and 17% – 31% show $W_{\lambda}^{\text{rest}} > 190 \text{ \AA}$ (93% confidence). Furthermore, the narrow velocity widths ($\Delta v < 500 \text{ km s}^{-1}$) together with a lack of high-ionization state emission lines support the conclusion that the Ly α 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 Ly α line) dictates that though these galaxies are young, they show no evidence of being truly primitive, Population III objects. We also find that the Ly α lines in this sample systematically disfavor combinations of low velocity width ($< 150 \text{ km s}^{-1}$) and high luminosity ($> 5 \times 10^{42} \text{ erg s}^{-1}$), suggesting that more than dust content alone, it is the velocity structure of a galaxy that determines the detectability of Ly α in emission. Finally, we construct a luminosity function of $z \approx 4.5$ Ly α emission lines for comparison to a set of Ly α luminosity functions spanning $3.1 < z < 6.6$. We conclude that if there is evolution in the Ly α 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 Ly α -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*

Contents

List of Figures	vii
List of Tables	ix
Acknowledgments	xi
1 Introduction: The Failed Search for Primeval Galaxies	1
1.1 History: Breaching the Realm of the Nebulae	2
1.2 The Race to High Redshift	4
1.3 Emission-Line Selection	8
1.3.1 Serendipitous Slit Spectroscopy	11
1.3.2 Narrowband Imaging	12
1.4 Thesis Overview	13
I Serendipitous Slit Spectroscopy	15
2 Serendipitously Detected Galaxies in the HDF	17
2.1 Introduction	18
2.2 Observations and Data Reductions	20
2.3 Visual Identifications and Redshift Determinations	22
2.3.1 Visual Identifications	22
2.3.2 Redshifts	24
2.4 The Catalogs	29
2.5 Discussion	30
2.5.1 The Redshift Distribution	31
2.5.2 A Check of Photometric Redshifts	32
2.5.3 A Galaxy Cluster at $z = 0.85$	35
2.5.4 Spectroscopy of the X-ray Source CXOHDFN J123635.6+621424 . .	36
2.5.5 Galaxies at $z > 5$	39
2.6 Conclusion	42
3 A Galactic Wind at $z = 5.190$	51
3.1 Introduction	52
3.2 Observation and Data Reduction	53

3.3	Properties of the Ly α Emission Line	58
3.3.1	The Emission Line Luminosity & Equivalent Width	58
3.3.2	Modeling the Emission Line	60
3.4	Discussion and Conclusion	63
4	A High-Redshift, Hard X-ray Emitting Spiral Galaxy	69
4.1	Introduction	70
4.2	Spectroscopic Observations	73
4.2.1	Optical Spectroscopy	73
4.2.2	Near-Infrared Spectroscopy	74
4.3	HDFX28 as a Type II AGN	78
4.3.1	Results from the Optical Spectrum	78
4.3.2	Results from the Near-Infrared Spectrum	81
4.3.3	Results from the Multi-Wavelength Photometry	83
4.4	HDFX28 as a High-Redshift Spiral Galaxy	86
4.5	Conclusion	89
II	Narrow Band Imaging Selection	95
5	Spectroscopic Properties of the $z \approx 4.5$ Lyα-emitters	97
5.1	Introduction	98
5.2	Observations	99
5.2.1	Narrowband and Broadband Imaging	99
5.2.2	Spectroscopic Observations	100
5.3	Spectroscopic Results	101
5.3.1	Results from the 400 ℓ /mm-Grating Observations	102
5.3.2	Results from the 150 ℓ /mm-Grating Observations	107
5.3.3	Spectroscopic Non-Detections	110
5.4	Discussion	110
5.4.1	The Statistics of the $z = 4.5$ Population	110
5.4.2	The Equivalent Width Distribution	111
5.4.3	AGN Among the $z \approx 4.5$ Population?	113
5.4.4	Population III Among the $z \approx 4.5$ Population?	114
5.5	Conclusion	116
6	A Lyα Luminosity Function at $z \approx 4.5$	121
6.1	Introduction	122
6.2	Observations	124
6.2.1	Narrowband and Broadband Imaging	124
6.2.2	Spectroscopic Observations	124
6.3	Spectroscopic Results	126
6.3.1	Spectroscopic Sensitivity to Ly α Emission	129
6.3.2	Redshift Identification	133
6.4	Discussion	135
6.4.1	The Equivalent Width and Velocity Width Distributions	136

6.4.2	Empirical Cumulative Luminosity Function	140
6.4.3	The V/V_{\max} Estimate	142
6.4.4	Comparison to LBGs	147
6.4.5	Implications for Reionization	149
6.5	Conclusion	150
7	Conclusion	157
7.1	Connecting Galaxy Populations	158
7.2	The Physical Nature of the Ly α -Emitting Galaxies	159
7.3	Host Dark Matter Halos	161
7.4	The History of Reionization	162
7.5	Results of Pilot Study	164
	Bibliography	165

List of Figures

1.1	Radio spectral energy distribution of Cygnus A.	5
1.2	Model star-forming galaxy at $z = 3.151$	6
1.3	Example of a $z \approx 4$ B -band “drop-out” galaxy in the Pisces field.	7
1.4	Distribution of I -band continuum flux for narrowband-selected Ly α -emitting galaxies in the LALA survey, and for photometrically-selected Lyman-break galaxies in the NOAO Deep Wide-Field Survey.	9
1.5	Survey volumes for complementary emission-line search strategies.	10
1.6	Night-sky emission spectrum overlaid with sample narrowband and broadband comparison filters typical of searches for high-redshift Ly α	12
2.1	Example spectra for spectral categories 1, 2, and 3.	26
2.2	Example spectra for spectral category 4.	27
2.3	Example spectra for spectral category 5.	28
2.4	Distribution of redshifts for the serendipitous sample.	30
2.5	Distribution of redshifts for the serendipitous sample over the range $0 < z < 1$	31
2.6	Comparison of spectroscopic and photometric redshifts.	34
2.7	Optical spectrum of the X-ray source CXOHDFN J123635.6+621424.	38
2.8	Discovery spectrogram for F 36246–1511, a solo emission line source interpreted as a Ly α -emitter at $z = 5.631$	40
2.9	The one-dimensional extracted spectrum of F 36246–1511.	41
3.1	ES1 discovery spectrum.	54
3.2	Central region of the HST I_{814} mosaic of the Hubble Deep Field North West Flanking Field.	55
3.3	Ground-based supporting imaging for ES1.	57
3.4	Ly α emission line luminosity vs. redshift for 13 Ly α -emitting galaxies.	59
3.5	The minimum- χ^2 fit to the ES1 Ly α emission line.	62
3.6	The relationship between the displacement velocity and the width of the broad emission component.	64
3.7	Composite spectrum of four galaxies at $z > 4.5$	66
4.1	Central portion of the HDF Inner West Flanking Field, centered on HDFX28.	72
4.2	Blue channel optical spectrum of HDFX28.	75
4.3	Red channel optical spectrum of HDFX28.	76

4.4	Near-infrared spectrum of HDFX28.	77
4.5	The N 5 λ 1240 / C 4 λ 1549 vs. N 5 λ 1240 / He 2 λ 1640 plane.	80
5.1	Spectra of the 11 confirmed $z \approx 4.5$ galaxies observed with the Keck/LRIS 400 ℓ /mm-grating.	103
5.2	Spectra of the 7 confirmed $z \approx 4.5$ galaxies observed with the Keck/LRIS 150 ℓ /mm-grating.	104
5.3	Scatter plot of the flux-based asymmetry statistic a_f vs. the wavelength-based asymmetry statistic a_λ	106
5.4	Composite spectrum consisting of an unweighted coaddition of the 11 $z \approx 4.5$ galaxies confirmed in 400 ℓ /mm-grating observations.	108
5.5	Composite spectrum consisting of an unweighted coaddition of the 7 $z \approx 4.5$ galaxies confirmed in 150 ℓ /mm-grating observations.	109
5.6	Histogram of the spectroscopic rest frame equivalent widths for the $z \approx 4.5$ population.	112
6.1	Distribution of redshifts for spectroscopically confirmed Ly α emission lines in the Cetus and Boötes fields.	126
6.2	Sample spectra from the set of 59 $z \approx 4.5$ Ly α -emitting galaxies confirmed with Keck/DEIMOS.	127
6.3	Spectroscopic success rate as a function of narrowband flux.	130
6.4	Empirical, cumulative distribution of spectroscopic sensitivity to Ly α emission, as a function of source redshift and Ly α flux.	131
6.5	Sample Ly α emission line profile compared to two common low-redshift interlopers.	132
6.6	Scatter plot comparing the flux-based asymmetry statistic a_f and the wavelength-based asymmetry statistic a_λ	134
6.7	Histogram of the spectroscopic rest-frame equivalent widths for the $z \approx 4.5$ population.	137
6.8	Scatter plot of velocity widths and luminosities of the $z \approx 4.5$ Ly α emission lines.	139
6.9	Comparison of empirical, cumulative Ly α luminosity functions for several spectroscopic surveys spanning $3.1 < z < 6.6$	141
6.10	Probability as a function of narrowband flux that a candidate Ly α -emitter was targeted for spectroscopy.	143
6.11	Ly α luminosity functions computed with the V/V_{\max} method for several spectroscopic surveys spanning $3.1 < z < 6.6$	146

List of Tables

2.1	Spectral Categories for Serendipitous Detections	44
2.2	Serendipitously Detected Galaxies in the Central HDF	45
2.3	Serendipitously Detected Galaxies Outside of the Central HDF	47
2.4	Summary of Properties of Spectroscopic Members of ClG 1236+6215	49
3.1	ES1 Ly α Line Model Parameters	68
3.2	ES1 Ground-Based Photometry	68
4.1	Emission-Line Measurements of HDFX28	92
4.2	Diagnostic Emission-Line Ratios	93
4.3	Photometry of HDFX28	94
5.1	Spectroscopic Properties of the Keck/LRIS $z \approx 4.5$ Ly α -Emitters	119
6.1	Spectroscopic Properties of the Keck/DEIMOS $z \approx 4.5$ Ly α -Emitters	152
6.2	Schechter Function Fit Parameters	155

Acknowledgments

I owe incalculable debts of gratitude to my forebears along two distinct lines of heredity: one academic, one biological. My advisor, Hy Spinrad, is the patriarch of a vast family tree of astronomers, of which I am the last of the line. I wish to thank Hy not only for the intellectual freedom he afforded me and for the scientific insights he offered, but also for allying me, as my intellectual father, to his former students, my intellectual older brothers. In ascending order: Dan Stern taught me literally everything I know about observing. Arjun Dey, with his apparently limitless erudition, taught me nearly everything else. More importantly, with major contributions from Mark Dickinson, the Spinradians taught me how to enjoy myself as a scientist, to prioritize scuba diving, record shopping, and ultimate frisbee right alongside the acquisition of data. My academic family tree also harbors a few wacky cousins, uncles, and neighbors: I benefited greatly both personally and scientifically from guidance and/or comic relief provided by Wil van Breugel, Andy Bunker, Mark Lacy, Wim de Vries, Michiel Reuland, Steve Croft, Buell Jannuzi, James Rhoads, and Sangeeta Malhotra.

I owe humble thanks of at least equal magnitude to the members of my literal family tree. My parents have been unflagging in their support of my long academic career. My admiration for the adroitness with which they match high expectations with unconditional acceptance is boundless. My sister has been a model of both industry and empathy as she pursues her own Ph.D.; thankfully, our periodic urges to chuck it all were never in phase. It's a simple fact that I would neither have pursued a Ph.D., nor stuck with it, if my father hadn't provided the model (along with occasional bursts of zen-like wisdom), my mother hadn't provided the financial, emotional, and motivational support, or if my sister hadn't provided the tiniest edge of sibling rivalry.

Finally, it is essential that I acknowledge that any shred of perspective or sanity I retained throughout this experience is owed to those folks I am so grateful to call my

friends. Spanning elementary school to the present, Danny Ronen, Angie Conley, Jon Klein, Kim Decker, Liz Green, Gina Rappleye, Rob Badzey, Todd Schweisinger, Lindsey Westbrook, and Pat Garvey were separately and collectively critical in helping me to weather the tribulations of the past decade, and were indefatigable in celebrating the successes. In addition, a handful of the denizens of Campbell Hall (and their spouses) transcended mere astronomy and became great friends in their own right, namely Julie Walters, Megan Eckart, Tim Robishaw, Erin & John Johnson, and the founding members of the Astronomy Student Society (Alison Coil, Dave Sherfese, Josh Simon, and Jon Swift). And speaking of mysterious societies, the members of the following eclectic associations provided endless distraction and affection: the Blue Bombers (Peter & Erin Marietta, Yurah & Andrew Yen, Kelly Givner, Andrea Barton–Elson, and Rachel Zimmerman); the Tower House Gang and its tangled legacy (e.g. Kris & Sammy Ahmed, and Ian Farrell), the Delicate Flower, Po', Rock Club, and the Mixturbators. And where would I be without the warm support of Sarah McCarthy, and her mixes, and her brunches? Thank you for reminding me that there is life to be had outside of this office.

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 Ly α 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 Ly α emission which would signify the expected widespread population of galaxies undergoing their first starbursts. Though a handful of Ly α -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 anomalous 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 Ly α had achieved flux levels and survey volumes which, according to simple models, ought to have detected thousands of objects (Pritchett 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 Ly α -emitters, albeit with Ly α 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 Ly α emission lines utilizing two observational techniques: serendipitous slit spectroscopy and narrowband imaging. By pushing these techniques to their utmost limits, we probe the Ly α -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 -cosmology¹, with $\Omega_{\text{M}} = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, 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

¹Unless 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.