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Spectroscopy of galaxies in the Bootes Void

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**SPECTROSCOPY OF GALAXIES
IN THE BOOTES VOID**

by

Shawn Timothy Cruzen

**A dissertation submitted in partial fulfillment
of the requirements for the degree of**

Doctor of Philosophy

in

Physics

**Department of Physics
University of Nevada, Las Vegas
August 1997**

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August 1997

ABSTRACT

The goal of this project is to investigate the physical properties of a sample of galaxies in the Bootes Void, and to classify these galaxies based on the properties of emission lines in their spectra. The spectra of 26 galaxies in the Bootes Void are analyzed. Fourteen galaxies are classified as HII galaxies with properties similar to field HII galaxies. Two of these galaxies, 1432+5302 and 1507+4554, are classified as extreme starburst (ESB) galaxies. Approximately 48% of the galaxies with measurable $H\alpha$ + $[NII]$ emission have elevated rates of star formation, based on equivalent widths. Continuum shapes and color indices are in good agreement with photometric results. Analysis of the galaxy continua suggest that approximately 1/3 of the void galaxies have large populations of blue stars. Stellar absorption features are observed in over half the galaxies in the sample, implying the presence of older, higher-metallicity stars.

Emission lines are detected from the HI galaxy 1517+3949 for the first time. Two systems, 1510+4727 and 1517+3956, are identified as merging or closely interacting galaxy pairs, bringing the total number of known galaxy pairs in the void to four. The galaxy 1458+4944 is found to be a LINER, making at least five AGNs in the void. Classifications of eight galaxies in the sample remain unknown. No emission lines were detected from three galaxies, 1503+5428, 1535+3831 and

1537+5315. Upper limits on line emission from each of these three galaxies are defined.

The galaxies in the Bootes Void are shown to be similar to emission line galaxies in the field with respect to stellar populations, emission line properties, fraction of AGNs and fraction of galaxy pairs. This result is inconsistent with some models of galaxy formation in low-density environments.

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CHAPTER 1

INTRODUCTION

Understanding the role that environment plays in the process of galaxy formation and evolution is one of the most important problems in astrophysics. Observations of the physical characteristics of galaxies in various environments has led to morphology-density relations such as those proposed by Dressler (1980); Postman & Geller (1984) and Giovanelli, Haynes & Chincarini (1986). These studies have shown that the population fraction of galaxies with different morphological types varies strongly with the space density of galaxies (galaxies Mpc^{-3}) over several orders of magnitude. In general, the relative numbers of S0 and elliptical galaxies increase with space density, while the fractions of spiral and irregular galaxies decrease. Although much of the work in this area has emphasized cluster populations, the environmental influence on the formation of galaxies in low density regions must also be understood for the model to be complete. Investigations into the properties of galaxies in low density regions will provide useful information on the role of environment in galaxy formation and evolution.

The data from galaxy redshift surveys such as the CfA slice (de Lapparent, Geller & Huchra 1986) and others (e.g. Tifft & Gregory 1976, 1988) have shown

the existence of large regions of low density in the spatial distribution of galaxies. These regions appear to be characteristic of the large scale structure of the universe and to be arranged in a hierarchical system of voids and supervoids (Lindner et al. 1995). A reconstruction of the nearby matter density field by da Costa et al. (1996), in which the peculiar velocities of late-type spirals were derived from the Tully-Fisher relation, has shown that these deficiencies in the distribution of galaxies delineate real voids in the underlying distribution of matter, and that these voids are more abundant than previous work had shown.

My collaborators (D. Weistrop, R. Angione & C. Hoopes) and I have undertaken an on-going program to study the physical nature of galaxies which have evolved in these low-density environments, or voids. This work is the second phase of a project to characterize a sample of 27 galaxies in the large void which lies in the direction of the constellation Bootes (the sample is discussed in Chapter 2).

The existence of the Bootes Void was first proposed by Kirshner et al. (1981). Based on data from a redshift survey in the direction of the north galactic cap, Kirshner et al. identified a $3.1 \times 10^5 \text{ Mpc}^3$ void ($H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, adopted throughout) in the galaxy distribution centered at $\text{RA} = 14^{\text{h}}50^{\text{m}}$, $\text{Dec} = +46^\circ$, $v = 15,500 \text{ km/sec}$, corresponding to a redshift range of $z = 0.041$ to $z = 0.062$.

The same group later used a pencil-beam survey to better sample the galaxy distribution within the region (Kirshner et al. 1987). Galaxies were chosen from 283 small fields (15' on a side) arranged in a grid which spanned the void boundaries. This arrangement sampled approximately 2% of the area of the grid (less than 3% of the actual void volume). Spectra were obtained and redshifts were measured for 239

galaxies lying in the direction of the void. No normal galaxies (galaxies without strong emission lines) were found from this sample within a spherical region of radius 42 Mpc centered on the above coordinates. Only two emission line galaxies whose redshifts had been previously determined (I Zw 81 and Mrk 845) were known to be within this region. Approximately 31 normal galaxies were expected if the sample distribution had been similar to that of the field galaxy distribution. From this result, Kirshner et al. concluded there was only a 1% chance that the density of normal galaxies in the void is higher than 25% of the cosmic mean density. This conclusion confirmed the existence of the large region of low density, now known as the Bootes Void.

Since the time of its discovery, several more galaxies have been identified within the Bootes Void (see Chapter 2). The void population includes both emission line galaxies and galaxies with strong infrared emission detected by IRAS (Infrared Astronomical Satellite). The number density of bright emission line galaxies in the Bootes Void is estimated to be only about one third that of the field distribution of bright emission line galaxies (Weistrop 1989). The number density of IRAS galaxies in the void is between 1/3 and 1/6 that of the normal density of IRAS galaxies having the highest flux quality at 60 μm (Dey et al. 1990). These estimates of the density in the void are consistent with the calculation of Kirshner et al. (1987).

In the first phase of the project to investigate the Bootes Void galaxies, we obtained photometric imaging of the sample of 27 galaxies in broadband BVRI filters. From these data, the magnitudes and colors of the galaxies were calculated, and the morphological properties were examined. The results of this imaging survey

(Cruzen, Weistrop & Hoopes 1997, hereafter C97) will be included in the following discussion of these galaxies.

In this second phase of the project, we have conducted a long-slit spectroscopic survey of our sample of galaxies in the Bootes Void. Peimbert and Torres-Peimbert (1992, hereafter PTP) have presented spectrophotometry for ten of these galaxies. However, spectra for most of our sample have not been published, nor have their emission line characteristics been thoroughly discussed. We have obtained spectra for 24 of the 27 galaxies in our original sample. Spectra for the remaining three galaxies have been published elsewhere, and will be included in this discussion.

The goal of this project is to analyze the spectroscopic data from our sample of Bootes Void galaxies in order to better understand the physical properties of the galaxies, as well as the energetic processes taking place within them. The fluxes, equivalent widths and relative intensities of emission lines from these galaxies are examined to investigate the source of the ionizing radiation and the ionization state of their gaseous components. These data are used to determine whether a galaxy is undergoing an episode of increased star formation, or possibly contains an active galactic nucleus (AGN). Spectral absorption features, as well as the overall shape of the continuum, are examined to characterize the stellar populations within the galaxies. These characteristics are compared to the results from the photometric survey. The results from these analyses will help to classify the sample of Bootes Void galaxies, which will provide further constraints on the models of galaxy formation in low-density environments.

In Chapter 2, our sample of Bootes Void galaxies is defined. The observations and data reductions are described in Chapters 3 & 4, respectively. Techniques for analyzing the data are described in Chapter 5. Detailed individual descriptions of the emission line properties of each galaxy in our sample are given in Chapter 6. Additional analysis leading to the classification of two systems in our sample as merging or closely interacting galaxy pairs is discussed in Chapter 7. Chapter 8 is a review of the results from the analysis. Chapter 9 contains a brief summary of the conclusions and a discussion of the context of the results from both phases of the project.

CHAPTER 2

THE GALAXY SAMPLE

Our sample is defined as the 27 galaxies which were known to lie in the Bootes Void when this project began in 1993 (see Table 1). Since then, additional Bootes Void galaxies have been reported by Aldering et al. (1995) and Szomoru et al. (1996, hereafter known as S96). The 18 galaxies of S96 (which are not included in our sample) were identified in an HI survey of the region. Identification for one of these HI galaxies was published earlier by Szomoru et al. (1993), and this galaxy is included in our sample.

Aldering et al. (1995) identified galaxies in the Bootes Void by selecting objects from the IRAS Faint Source Survey. These authors have not yet published identifications of their galaxies and the total number in their sample is not known, although 12 are discussed by S96.

At least 26 of the 27 galaxies in our sample are emission line galaxies (Tifft et al. 1986, Moody et al. 1987, Weistrop & Downes, 1988, Strauss & Huchra, 1988, Weistrop 1989, Dey et al. 1990, Schneider et al. 1994). These 26 emission line galaxies were found to lie within the void by follow-up spectroscopic observations of galaxies identified from either the IRAS Point Source Catalog (PSC, 1985) or

low-dispersion spectroscopic surveys, primarily the Case Low-Dispersion Northern Sky Survey (Sanduleak & Pesch 1987, 1989, and Pesch & Sanduleak 1989, hereafter referred to as the Case Survey). References for the identification of each Bootes Void galaxy are listed in Table 1 (col. 3).

Many of the galaxies identified in the Case Survey were selected due to the presence of emission lines in the low-dispersion spectra. These emission lines are energized either by the radiation of hot, young O and B stars, or by the hard, non-thermal emission spectra of active galactic nuclei. IRAS detections select galaxies with large concentrations of warm dust, which are also associated with recent star formation or active nuclei. Therefore, galaxies identified by infrared surveys tend to be emission line galaxies and are likely to be experiencing star formation, nuclear activity, or possibly a combination. These selection effects must be considered when examining the group properties of our sample.

The subsample of void galaxies identified in low-dispersion spectroscopic surveys does not represent a complete sample because follow-up spectra of all candidate objects from the Case Survey have not been obtained. In addition, the galaxies identified by Schneider, Schmidt & Gunn (1994, hereafter SSG) were from a fainter redshift survey than the Case Survey causing another nonuniformity in this subsample. Thus, the sample of 27 galaxies is also not complete. The subsample of IRAS galaxies is complete above 60 μm flux densities of 0.6 Jy, but is not complete below 0.6 Jy (Dey et al. 1990).

The galaxy 1517+3949, identified in the HI survey by Szomoru et al. (1993), is the only galaxy in the sample not identified either by low-dispersion spectroscopy

or from the IRAS PSC. Based on the position of the galaxy on the sky and the HI redshift, Szomoru et al. report this galaxy to be associated with the emission line object 1517+3956.

TABLE 1. Summary of spectroscopic data for the Bootes Void galaxies.

Galaxy	ID	Ref.	c	H δ	H γ	[OIII] λ 4363	Flux (λ) / Flux (5500 $\text{\AA}$)					HeI λ 5876	[OI] λ 6300
							H β	[OIII] λ 4959	[OIII] λ 5007	(10)	(11)		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)		
1345+4641		8	---	---	---	---	---	---	---	---	---	---	---
1357+4641		8	2.24	---	---	---	8.40 $\pm$ 0.61	12.90 $\pm$ 0.61	21.85 $\pm$ 0.54	---	---	---	---
1406+4905	I Zw 81	1	2.44	---	---	---	3.02 $\pm$ 0.36	2.78 $\pm$ 0.16	5.71 $\pm$ 0.15	---	---	---	---
1407+4840	CG 910	5	---	---	---	---	---	---	---	---	---	---	---
1408+4852	CG 370	6	0.70*	---	6.62 $\pm$ 0.35	---	12.71 $\pm$ 0.30	10.52 $\pm$ 0.27	26.22 $\pm$ 0.30	3.60 $\pm$ 0.21	1.34 $\pm$ 0.18	---	---
1413+5056		7	---	---	---	---	---	---	---	---	---	---	---
1428+5255		5	---	---	---	---	---	2.60 $\pm$ 0.21	2.99 $\pm$ 0.18	---	---	---	---
1432+5302	CG 474	4	0.50*	8.60 $\pm$ 0.88	24.06 $\pm$ 0.41	2.46 $\pm$ 0.25	50.22 $\pm$ 0.45	56.48 $\pm$ 0.44	174.69 $\pm$ 0.64	6.54 $\pm$ 0.29	3.62 $\pm$ 0.29	---	---
1444+4402	CG 538	7	2.70	---	---	---	4.07 $\pm$ 0.19	0.67 $\pm$ 0.22	1.02 $\pm$ 0.09	---	---	---	---
1446+4457	CG 547	3	0.67*	---	3.11 $\pm$ 0.45	---	5.52 $\pm$ 0.21	5.64 $\pm$ 0.16	9.76 $\pm$ 0.16	1.48 $\pm$ 0.13	1.03 $\pm$ 0.11	---	---
1457+4228	CG 598	2	2.46	---	---	---	7.61 $\pm$ 0.21	4.37 $\pm$ 0.18	10.40 $\pm$ 0.16	---	---	---	---
1458+4944	CG 922	9	0.44	---	7.84 $\pm$ 0.47	---	14.15 $\pm$ 0.42	9.87 $\pm$ 0.39	25.21 $\pm$ 0.43	---	---	---	---
1503+5428	CG 620	9	---	---	---	---	---	---	---	---	---	---	---
1505+3958	CG 629	6	1.75	---	---	---	3.21 $\pm$ 0.45	2.89 $\pm$ 0.26	4.89 $\pm$ 0.26	---	---	---	---
1506+5138	Mrk 845	3	---	---	---	---	---	4.26 $\pm$ 0.26	5.07 $\pm$ 0.20	---	---	---	---
1507+4554	CG 642	3	0.01*	35.40 $\pm$ 1.23	53.00 $\pm$ 1.49	---	117.20 $\pm$ 2.14	166.93 $\pm$ 2.54	469.33 $\pm$ 3.80	22.73 $\pm$ 1.47	---	---	---
1510+4727	CG 657	3	0.00	12.90 $\pm$ 0.44	30.88 $\pm$ 0.49	---	50.35 $\pm$ 0.59	77.80 $\pm$ 0.65	226.93 $\pm$ 0.99	7.50 $\pm$ 0.40	9.78 $\pm$ 0.63	---	---
1517+3949		10	---	---	---	---	---	6.09 $\pm$ 0.65	6.59 $\pm$ 0.60	---	---	---	---
1517+3956	CG 684	2	2.41*	---	10.10 $\pm$ 0.39	---	25.26 $\pm$ 0.29	18.31 $\pm$ 0.26	52.01 $\pm$ 0.31	1.96 $\pm$ 0.11	1.82 $\pm$ 0.11	---	---
1519+5050	CG 692	7	1.14*	---	7.19 $\pm$ 0.38	---	17.95 $\pm$ 0.31	7.49 $\pm$ 0.23	17.23 $\pm$ 0.27	---	---	---	---
1519+5050	CG 693	7	N/O	N/O	N/O	N/O	N/O	N/O	N/O	N/O	N/O	N/O	N/O
1530+4332	Main	7	1.47	---	---	---	6.36 $\pm$ 0.66	---	4.20 $\pm$ 0.59	---	---	---	---
1530+4332	Comp.	7	0.32	---	---	---	8.16 $\pm$ 0.59	5.06 $\pm$ 0.53	17.95 $\pm$ 0.54	---	---	---	---
1535+3831		7	---	---	---	---	---	---	---	---	---	---	---
1537+5315		7	---	---	---	---	---	---	---	---	---	---	---
1540+5013		7	---	---	---	---	---	---	---	---	---	---	---
1547+5121		5	2.07	---	---	---	5.06 $\pm$ 0.65	4.44 $\pm$ 0.44	7.19 $\pm$ 0.42	---	---	---	---

TABLE 1. (Continued)

Galaxy	Flux (λ)/Flux (5500 Å)					Equivalent Width (Å)						
	[OI] λ 6364	[NII] λ 6548	H α	[NII] λ 6583	[SII] λ 6717,31	H α + [NII]	G band	Mg b	Na D	41-50	F(5500 Å)	
(1)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	
1345+4641	---	---	42 $\pm$ 0.78	---	11.10 $\pm$ 0.71	-37.01 $\pm$ 0.67	---	---	---	---	0.10	
1357+4641	---	---	24.02 $\pm$ 0.30	---	4.72 $\pm$ 0.25	-44.41 $\pm$ 0.56	---	---	---	---	0.10	
1406+4905	---	2.03 $\pm$ 0.09	9.35 $\pm$ 0.23	6.16 $\pm$ 0.21	2.73 $\pm$ 0.09	-43.85 $\pm$ 0.28	2.35 $\pm$ 0.17	2.20 $\pm$ 0.15	---	0.16 $\pm$ 0.08	3.16	
1407+4840	---	4.14 $\pm$ 0.31	21.78 $\pm$ 0.53	12.21 $\pm$ 0.63	9.14 $\pm$ 0.32	-33.89 $\pm$ 0.30	---	2.23 $\pm$ 0.25	3.53 $\pm$ 0.18	0.64 $\pm$ 0.16	0.97	
1408+4852	2.65 $\pm$ 0.19	---	49.38 $\pm$ 1.08	---	13.78 $\pm$ 0.26	-74.07 $\pm$ 0.48	3.88 $\pm$ 0.27	---	---	0.18 $\pm$ 0.09	0.59	
1413+5056	---	---	13.04 $\pm$ 0.40	---	4.64 $\pm$ 0.31	-11.75 $\pm$ 0.36	4.92 $\pm$ 0.33	9.82 $\pm$ 0.95	---	0.72 $\pm$ 0.20	0.67	
1428+5255	---	4.55 $\pm$ 0.75	14.70 $\pm$ 0.97	6.60 $\pm$ 0.78	5.56 $\pm$ 0.38	-20.95 $\pm$ 0.29	7.20 $\pm$ 0.33	3.96 $\pm$ 0.28	3.42 $\pm$ 0.19	0.76 $\pm$ 0.13	2.50	
1432+5302	1.17 $\pm$ 0.21	3.93 $\pm$ 1.03	153.55 $\pm$ 3.06	11.92 $\pm$ 3.00	32.64 $\pm$ 0.42	-206.50 $\pm$ 0.78	---	---	---	-0.03 $\pm$ 0.08	1.02	
1444+4402	---	1.05 $\pm$ 0.09	11.64 $\pm$ 0.25	3.19 $\pm$ 0.23	2.95 $\pm$ 0.07	-49.91 $\pm$ 0.24	2.14 $\pm$ 0.15	---	---	0.43 $\pm$ 0.06	1.60	
1446+4457	0.63 $\pm$ 0.09	1.31 $\pm$ 0.21	26.75 $\pm$ 0.55	3.97 $\pm$ 0.51	8.79 $\pm$ 0.16	-45.13 $\pm$ 0.26	---	0.77 $\pm$ 0.11	---	0.28 $\pm$ 0.07	0.54	
1457+4228	---	2.00 $\pm$ 0.15	21.78 $\pm$ 0.44	6.07 $\pm$ 0.41	6.54 $\pm$ 0.09	-78.90 $\pm$ 0.34	---	---	---	0.24 $\pm$ 0.07	2.31	
1458+4944	---	7.64 $\pm$ 0.45	40.46 $\pm$ 1.72	23.14 $\pm$ 0.90	16.15 $\pm$ 0.50	-127.40 $\pm$ 1.09	1.01 $\pm$ 0.17	---	---	0.16 $\pm$ 0.09	0.95	
1503+5428	---	---	---	---	---	---	---	---	---	0.08 $\pm$ 0.56	0.13	
1505+3958	---	1.62 $\pm$ 0.15	9.18 $\pm$ 0.19	4.92 $\pm$ 0.22	4.14 $\pm$ 0.15	-29.98 $\pm$ 0.44	---	5.02 $\pm$ 0.37	---	0.34 $\pm$ 0.11	1.23	
1506+5138	---	3.41 $\pm$ 0.75	12.85 $\pm$ 0.56	4.01 $\pm$ 0.36	---	-16.10 $\pm$ 0.32	4.21 $\pm$ 0.27	5.93 $\pm$ 0.35	---	0.62 $\pm$ 0.10	1.03	
1507+4554	---	4.07 $\pm$ 2.33	305.53 $\pm$ 7.08	12.40 $\pm$ 6.33	62.27 $\pm$ 2.35	-455.00 $\pm$ 5.08	---	---	---	-0.12 $\pm$ 0.35	1.52	
1510+4727	7.35 $\pm$ 0.69	21.23 $\pm$ 1.04	135.25 $\pm$ 2.86	64.35 $\pm$ 2.77	26.70 $\pm$ 0.61	-406.50 $\pm$ 2.20	---	---	---	-0.12 $\pm$ 0.17	0.40	
1517+3949	---	0.28 $\pm$ 0.25	10.36 $\pm$ 0.75	0.82 $\pm$ 0.40	3.08 $\pm$ 0.27	-25.43 $\pm$ 0.85	---	---	---	0.39 $\pm$ 0.22	0.29	
1517+3956	0.64 $\pm$ 0.11	3.33 $\pm$ 0.30	46.11 $\pm$ 0.87	10.08 $\pm$ 0.85	13.94 $\pm$ 0.14	-154.00 $\pm$ 0.55	3.11 $\pm$ 0.23	1.82 $\pm$ 0.23	---	0.25 $\pm$ 0.08	0.92	
1519+5050	---	6.60 $\pm$ 0.27	32.90 $\pm$ 1.32	20.00 $\pm$ 0.66	8.37 $\pm$ 0.21	-131.60 $\pm$ 0.69	---	---	---	0.14 $\pm$ 0.10	1.09	
1519+5050	N/O	N/O	N/O	N/O	N/O	N/O	N/O	N/O	N/O	N/O	N/O	
1530+4332	---	2.98 $\pm$ 0.24	18.20 $\pm$ 0.81	9.04 $\pm$ 0.42	6.21 $\pm$ 0.23	-51.95 $\pm$ 0.59	9.02 $\pm$ 0.54	---	---	0.48 $\pm$ 0.19	0.77	
1530+4332	---	1.92 $\pm$ 0.60	23.32 $\pm$ 1.95	5.81 $\pm$ 1.26	7.08 $\pm$ 0.58	-50.22 $\pm$ 1.16	6.86 $\pm$ 0.50	---	---	0.21 $\pm$ 0.24	0.45	
1535+3831	---	---	---	---	---	---	---	---	---	0.30 $\pm$ 0.11	0.92	
1537+5315	---	---	---	---	---	---	---	---	---	0.30 $\pm$ 0.22	0.87	
1540+5013	---	---	20.53 $\pm$ 0.30	---	---	23.85 $\pm$ 0.35	2.78 $\pm$ 0.26	---	---	0.61 $\pm$ 0.14	1.30	
1547+5121	---	1.31 $\pm$ 0.22	14.46 $\pm$ 0.66	3.96 $\pm$ 0.35	5.12 $\pm$ 0.29	-46.58 $\pm$ 0.70	---	2.39 $\pm$ 0.40	4.45 $\pm$ 0.51	0.28 $\pm$ 0.23	0.54	

Notes to TABLE 1.

The uncertainties for the measured quantities are given next to the values. Column (1) -galaxy designation; column (2) - alternate identifications for the galaxies; column (3) - number for discovery paper (below); column (4) - reddening correction parameter. The * indicates values of c calculated from both $H\alpha/H\beta$ & $H\gamma/H\beta$; columns (5)-(17) - fluxes of emission lines normalized to the flux at the reference wavelength of $5500 \text{ \AA}$; column (18) - equivalent width of the $H\alpha+[NII]$ complex in $\text{\AA}$; columns (19)-(21) - equivalent widths of stellar absorption features in $\text{\AA}$; column (22) - 41-50 continuum color index; column (23) - Flux at $5500 \text{ \AA}$ in units of $10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$. N/O $\equiv$ galaxy not observed.

References for Galaxies: 1 Sargent (1970); 2 Tifft et al. (1986); 3 Moody et al. (1987); 4 Weistrop & Downes (1988); 5 Strauss & Huchra (1988); 6 Weistrop (1989); 7 Dey et al. (1990); 8 Schneider et al. (1994); 9 Lipovetsky (see Weistrop et al. 1995); 10 Szomoru et al. (1993); 11 Weistrop et al. (1992).

CHAPTER 3

OBSERVATIONS

We obtained spectra of 24 Bootes Void galaxies using the 40-inch telescope at Mt. Laguna Observatory in Mount Laguna, CA. Mount Laguna Observatory is operated jointly by San Diego State University and the University of Illinois. These observations were made on three observing runs; 1993 May 22-26 U.T., 1994 May 11-15 U.T., and 1995 May 21-24 U.T. Not all of these nights were photometric. Data taken on non-photometric nights are indicated in Table 2.

The spectra were taken using the CCD grism spectrograph, with the 50 mm focal reducer. In this configuration, the TI CCD with an 800x800 pixel format has a range of approximately 4000 Å - 7500 Å, with a scale of 6.7 Å/pixel and a spectral resolution of approximately 18 Å. The wavelength range is somewhat adjustable. The slit width is 4".5 - 5", approximately 3 pixels on the CCD. The spatial scale on the CCD is 1".56/pixel.

When performing CCD spectroscopy it is necessary to perform a variety of calibrations to remove the effects of the electronics in the detector from the data. Various sets of data must be acquired at the telescope so that these calibrations may

TABLE 2. Observing Summary

U.T. Date	Photometric	Galaxy	ID	Integrations
1993 May 25	Yes	1407+4840	CG 910	3
		1428+5255		2
		1530+4332	(Pair)	3
		1517+3956	CG 684	
			(North)	1
			(South)	2
1993 May 26	No	1547+5121		2
		1540+5013		2
		1519+5050	CG 692	2
1994 May 13	No	1406+4905	I Zw 81	3
		1413+5056		3
		1537+5315		3
1994 May 14	Yes	1408+4852	CG 370	3
		1444+4402	CG 538	3
		1510+4727	CG 657	3
		1535+3831		3
		1506+5138	Mrk 845	3
1994 May 15	Yes	1432+5302	CG 474	3
		1446+4457	CG 547	3
		1457+4228	CG 598	3
		1505+3958	CG 629	3
		1458+4944	CG 922	3
1995 May 21	No	1517+3949		3
		1503+5428	CG 620	3
		1507+4554	CG 642	3
1995 May 24	No	1510+4727	CG 657	
			(North)	2
			(South)	2

TABLE 2. All observations were made using the CCD grism spectrograph on the 40-inch telescope at Mount Laguna Observatory. The integration times were all 20 minutes. Column (1) indicates the nights on which data were taken. Column (2) denotes whether or not the night was photometric. Column (3) lists the galaxies observed on a given night. Column (4) gives alternate identifications (if any) for galaxies observed. Column (5) lists the number of integrations taken for each galaxy.

be performed. The calibrations acquired for this data set include an overscan region, bias frames and flat field images.

Data are retrieved from CCD's by transferring the charge in each pixel across the chip to the readout amplifier located at one corner. A fraction of the charge is lost in this process. The ratio of the charge received by the amplifier to the charge originally placed on the chip is defined as a charge transfer efficiency (CTE).

When the charge on the CCD is small, the CTE increases as the amount of charge increases. Because of this affect, a pedestal of charge is added to the chip before each exposure to increase the CTE. All images contain this base level of counts. It is subtracted from the data during data reduction.

To determine the magnitude of this pedestal in our data, a region of the CCD was not exposed to light, and therefore contained only the number of counts corresponding to the base level. On the Mount Laguna TI CCD, this region, defined as the overscan region, is 20 columns of pixels at one end of the chip.

The two types of calibration images applied to these data are bias frames and flat field images. These images are used to remove the effects of the pixel to pixel sensitivity variations and other types of spatially systematic errors across the chip.

A bias frame is a zero-second exposure which acts as a map of the additive stationary pattern introduced into each image by the camera electronics. A flat field image is used to correct for quantum efficiency and optical transmission variations across the CCD. In essence, this is a measure of the sensitivity with which each pixel responds to light as a function of wavelength. Therefore, the flat field

correction will involve dividing the measured signal in each pixel by some fraction which represents the sensitivity of that pixel.

To perform these corrections on our data, sets of zero-second exposures were taken to record the structure in the bias for each night. Changes in the bias level of the CCD over the course of the night were found to be negligible. These frames were later combined using a median filter into a median bias frame for each night.

Flat field frames were obtained by observing a continuum light-source projected through a KG1 filter onto a screen on the inside of the dome. Two to three of these dome flats were taken each night through the grism. The exposure times for the dome flats were adjusted so that the maximum number of counts per pixel above the bias level was between 3000 and 8000 counts. This range of counts was chosen to yield good statistics but still be below the point at which the CCD no longer responds linearly.

Another set of calibration images was taken in order to perform a wavelength calibration (or dispersion correction) on the reduced spectra of the galaxies and standard stars. Helium, neon and argon calibration lamps were placed to project light onto the screen on the inside of the dome. The telescope was pointed at the screen and spectra were taken of each calibration lamp. Additional spectra of the argon lamp were taken with the broadband B filter in place in order to suppress the red end of the spectrum. The filter allowed longer exposures to be taken so that the positions of the argon lines present on the blue end of the available wavelength range could be measured more easily. These images will be referred to as the argon-blue frames. The wavelengths of the emission lines produced by the calibration

lamps are well known, and their positions on the CCD were used to derive a transformation from pixel position along the direction of the dispersion to wavelength (as described in Chapter 4).

Images of the slit were taken prior to taking any spectra of objects in order to determine the position of the slit on the CCD and the optimum location along the slit for the placement of the objects. Thus, before taking spectra of standard stars or galaxies, the grism was removed from the light path and direct images were taken in order to insure that the objects were properly aligned with the slit position. The orientation of the slit was fixed corresponding to an east-west direction on the sky. Therefore, all spatial information in our data is east to west.

Standard stars from the list of Kitt Peak National Observatory spectrophotometric standards (Barnes & Hayes 1982), compiled for use with the Infrared Spectrometer, were observed on all nights. These observations were made near the beginning and end of the night. At least two standard stars were observed each night, and integrations times were typically 2 to 5 minutes. Spectra of these standard stars were used to correct for atmospheric extinction and to derive a conversion from the number of counts per pixel to flux in units of $\text{ergs cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ (Chapter 4).

When taking spectra of the galaxies, integration times of 20 minutes were used. Typically, three integrations were taken for each galaxy. Occasionally, our observing schedule only permitted two integrations per galaxy. The airmass range over which the galaxy spectra were taken was approximately 1.00 to 1.40.

CHAPTER 4

REDUCTIONS

The data were reduced using IRAF, the Interactive Reduction and Analysis Facility. Because the "image" produced by the spectrograph did not cover the entire CCD, the first step in the reduction process for these data was to determine what portion of the CCD contained usable data. The flat field images were examined to define the dimensions of the largest subsection within which the pixels contained a significant number of counts (approximately 10%) above the bias level. This subsection was defined as the image section, and all of the images on a given night were trimmed to this size.

Also during this reduction step, the base level of counts in the overscan region (the last 20 columns of the CCD) was subtracted by the following process. The number of counts in each row of the overscan region was averaged. A polynomial function of second order, running parallel to the columns, was fitted to these averaged values. This function defined the pedestal of counts which was subtracted from each image, including the bias and flat field frames. The average number of counts/pixel in the overscan region for these images was approximately 1400.

Once the images were trimmed and the overscan corrections had been made, all of the bias frames for a given night were combined, using a median filter, into a single bias calibration image. This combined bias was subtracted from all of the images and dome flats to correct for the additive stationary pattern in the CCD.

Next, the flat field images were combined. For nights when three dome flats were taken, a median filter was used. When only two dome flats were taken, the frames were averaged.

When dome flats are used for spectroscopic flat fields, they must be corrected for any systematic wavelength-dependent structure that is unique to the flat field. These peculiarities can be due to the spectral signature of the projector lamp, wavelength-dependent properties in the reflectivity of the screen, and transmission features in the filters used for color-balance. The standard corrections were made to the combined flat field images for each night using the IRAF task RESPONSE. This task is used to fit a low-order function to the flat field image along the dispersion axis, then to normalize the flat field by this smooth curve to remove any large-scale spectral signatures. The result is a flat field image with the structure in the wavelength direction due to the flat-field source removed. This process will also remove from the flat field some of the effects introduced by changes in the sensitivity of the CCD as a function of wavelength. Any remaining structure in the spectra due to the wavelength-dependent response of the CCD is removed during flux calibration (discussed below). Once this normalization was completed, flat-field corrections were performed on the images of the galaxies and the standard stars using the normalized flat field images.

After these basic reduction steps had been performed, one-dimensional spectra were extracted from the two-dimensional images. This operation was performed by summing all the rows along the dispersion axis within a given aperture. The number of rows contained within this aperture, referred to as the slit height, was determined by examining the profile of the two-dimensional spectrum along the spatial axis at various columns. The slit height was defined to be the width of the spatial profile at the point where the number of counts in the profile was 1% of its maximum value above the sky background. For example, if the maximum number of counts in the spatial profile was 600 and there were 100 counts in the sky, the slit height would be set equal to the separation of the two points in the profile corresponding to 105 counts.

Because of defocusing effects in the spectrograph, the ends of each spectrum had broader spatial profiles than the centers. The slit height was set at the end (broadest part) of each spectrum to ensure that little or no signal would be excluded from the one-dimensional spectrum. The larger slit heights allowed additional noise to be added to the center of the spectrum where the spatial profile was narrower. However, on average, the galaxy and standard star signals tended to be strong in this wavelength range, and this proved to be an acceptable compromise.

The night sky was subtracted from the spectra during the extraction process. The contribution from the night sky was measured in two small sub-apertures (approximately four pixels high), one on each side of the main extraction aperture. A minimum of two pixels for a buffer region was allowed between the main extraction aperture and the sub-apertures. A linear fit between the average counts

within these two sub-apertures was taken as the sky contribution. In multispec mode, IRAF allows the spectrum of the night-sky contribution to be saved into a separate one-dimensional output spectrum. This feature allows the night-sky contribution to be examined and the location of bright night-sky emission features to be determined.

After the extraction of one-dimensional spectra, a dispersion correction was performed. The first step in this process was to combine the two-dimensional images of the wavelength standards: helium, neon, argon, and argon-blue. The resulting images, referred to as the HeNeAr frames, were unique for each night of observing, and therefore were used only to calibrate spectra taken on the same night. For a given night, a set of one-dimensional reference spectra were extracted from the HeNeAr frame using the extraction apertures defined for the individual galaxies and standard stars.

The emission lines in the reference spectra were identified using the database of helium, neon and argon emission lines in IRAF. Once the lines had been identified in the reference spectra, they were checked against published spectra of similar calibration lamps and were found to match well.

Each reference spectrum was used to define a transformation from pixels to wavelength along the dispersion axis. Then, the dispersion in each one-dimensional spectrum of a galaxy or standard star was calibrated according to the wavelength solution derived from its unique reference spectrum. This was done to ensure that any variation of the position of the galaxy or standard star along the slit would not cause a systematic error in the wavelength calibration.

The accuracy of the dispersion correction was examined by measuring the positions of bright emission lines in the night-sky spectrum. It was determined that there were small, systematic errors in the measured wavelengths of the night-sky lines. These errors were probably due to changes in flexure within the optical system as the telescope position changed. The wavelength calibration lamps were observed at a much greater zenith distance than the galaxies or standard stars. The errors were corrected by setting the zero-point of the wavelength solution according to the positions of seven bright night-sky lines, which spanned most of the wavelength range of our spectra. These lines are listed in Table 3.

TABLE 3. Night Sky Lines

Wavelength (Å)	Source
4358.0	Hg I
5461.0	Hg I
5577.0	[OI]
5688.0	Na I
5890.0	Na I
6300.3	[OI]
6363.8	[OI]

The final step in the data reduction process is the flux calibration of the spectra, which includes a correction for atmospheric extinction. Extinction corrections were made by multiplying the data value in each pixel by a factor of $10^{0.4E(\lambda)A}$, where $E(\lambda)$ is the mean extinction coefficient at wavelength λ and A is the airmass. Because no extinction coefficients derived for Mount Laguna Observatory were available, the mean extinction coefficients for KPNO were used. These mean

coefficients were derived by many observers over a period of time, and are provided in IRAF. This method of extinction correction is not ideal, but it was the only option available.

Next, a wavelength-dependent sensitivity function for the optical system was derived for each night by measuring the number of counts per second observed within calibrated bandpasses from the set of spectrophotometric standard stars observed on that night. Because the expected fluxes from the standard stars are known for all of the calibrated bandpasses (and are contained in an IRAF database), a sensitivity function was derived by fitting a curve to the ratios of the observed to expected fluxes (expressed in magnitudes) as a function of wavelength. This sensitivity function was then applied to the galaxy spectra, converting intensities to energy flux in units of $\text{ergs cm}^{-2} \text{sec}^{-1} \text{\AA}^{-1}$. This process removes any remaining structure in the data, resulting from the CCD sensitivity, which was not fully corrected by the flat field division.

After the flux calibration process was complete, all of the spectra of a given galaxy were combined. When three spectra of a galaxy had been taken, the spectra were combined using a median filter. When only two spectra were taken, the spectra were averaged. For the remainder of this paper, these spectra are referred to collectively as the combined spectra.

CHAPTER 5

ANALYSIS TECHNIQUES

5.1 Identification and Measurement of Spectral Features

After the extracted spectra were calibrated and combined, a process was employed to identify spectral features. First, the published redshifts for the galaxies were identified from the literature (see C97). Most of the published redshifts had been corrected for the Sun's motion according to de Vaucouleurs et al. (1976)

$$(1) \quad z = z_0 + [300 (\sin l \cos b)/300,000]$$

where z_0 is the observed redshift, z is the corrected redshift, and l & b are the galactic longitude and latitude, respectively. These redshifts were transformed into the rest frame of the Earth by substituting the corrected redshifts for z and solving the equation for z_0 .

Next, the values of z_0 were used as initial references to determine the expected positions of the strongest emission features within each galaxy. The $H\alpha$ + $[NII]$ complex (the blended lines of $H \lambda 6563$ and $[NII] \lambda\lambda 6548, 6583$) was

identified in nearly all of the galaxies using this method. The exceptions were galaxies 1535+3831, 1537+5315 and 1503+5428, for which the spectra contained no detectable emission features.

A new reference redshift was determined for each galaxy from the position of the $H\alpha$ + $[NII]$ complex, and was used to identify other features within the combined spectrum. For many of the galaxies in our sample, other prominent emission features (for example $H\beta$, $[OIII] \lambda\lambda 4959, 5007$ & $[SII] \lambda\lambda 6717, 6731$) were obviously present upon inspection. For these galaxies, all of the obvious lines were used in the determination of the reference redshift.

Next, a list of spectral features (both absorption and emission lines) commonly detected in emission line galaxies (hereafter referred to as ELGs) was compiled. For each galaxy, the observed wavelengths of these suspected features were determined from the reference redshift. Then, the combined spectrum of the galaxy was examined at the predicted observed wavelengths to determine whether or not the features were present. A criterion for categorizing the detection of a line based on its associated uncertainty is discussed in Section 5.6

The line centers and equivalent widths (EW) of all the detected spectral features, and the fluxes in the emission lines were measured by direct integration using the IRAF task SPLIT. The local continuum level was determined interactively for each line by evaluating the mean of the continuum on either side of the line. These values served as the end-points for a linear estimation of the continuum underlying the feature. The full width at half-maximum (FWHM) of each emission line was estimated by fitting a Gaussian profile to the line.

5.2 Deblending of the $H\alpha$ + $[NII]$ Complex

To properly carry out various steps in the analysis of the spectra, such as reddening determination or diagnostics from emission line ratios, it is necessary to measure the flux in the $H\alpha$ line separately from the $[NII]$ $\lambda\lambda 6548, 6583$ doublet. Unfortunately, in our low-resolution spectra, these lines are badly blended and could not be satisfactorily deblended using the standard algorithms in IRAF. Therefore, an alternate method was designed to more precisely deblend the $H\alpha$ + $[NII]$ complex.

At a spectral resolution of $18 \text{ \AA}$, only broad $H\alpha$ lines with Doppler velocities $\geq 820 \text{ km/s}$ are resolved. Typically, this amount of broadening in the Balmer lines is only observed in Seyfert 1 galaxies. Because only a small fraction of ELGs are Seyfert 1's (Salzer et al. 1989), it is reasonable to assume that the $H\alpha$ lines in the majority of our galaxies are unresolved, and that the shapes of these lines correspond to the instrumental profile. In addition, if a galaxy had a broadened $H\alpha$ line, the $H\beta$ line would also be broadened. No broadening beyond the instrumental profile was observed for any of the $H\beta$ lines detected. The $[NII]$ lines in this complex are never broader than the $H\alpha$ line and, therefore, would also have instrumental profiles. Thus, we should be able to reproduce the line shape of the $H\alpha$ + $[NII]$ complex for a given galaxy by blending three template lines with instrumental profiles having the proper relative intensities, and at positions determined from the reference redshift.

The first step in the deblending procedure is to create a line template whose shape will represent the instrumental profile. The strong line at $7065 \text{ \AA}$, present in

all of the helium calibration spectra, was chosen for this purpose. The flux in this line was consistently over an order of magnitude greater than the flux in any of the emission lines from the galaxies, and thus had a relatively large signal to noise ratio (S/N).

An initial template was constructed by removing the helium line from the calibration spectrum, saving this modified image as a new image, and then subtracting the modified spectrum from the original helium spectrum. The resulting spectrum had an intensity of zero at all wavelengths except the position of the 7065 Å line. Then, this initial template was normalized to the peak intensity of the remaining line. A unique normalized template was created for each night on which data were taken. This was done to compensate for variations in the instrumental profile from night to night due to small fluctuations in the optical system and differences in focus.

To deblend spectra from a given night, three copies of the normalized template image were created. Each of the three templates were shifted so that the centers of the respective lines corresponded to the redshifted wavelengths of the H α and [NII] lines, with $z = 0.05$ (the redshift at the center of the Bootes Void). Because the theoretical ratio of the intensities in the [NII] doublet is known to be $[\lambda 6548/\lambda 6583] = 0.34$ (MacAlpine 1971), the normalized template for the $\lambda 6548$ line was multiplied by this factor. The modified $\lambda 6548$ template was then added to the $\lambda 6583$ template creating a single [NII] template with the proper relative intensities. Copies of the H α and [NII] templates were created for each galaxy

observed on that night, and were shifted to the proper positions according to the reference redshift for the respective galaxy.

Next, the local continuum level near the $H\alpha$ + $[NII]$ complex was subtracted from the combined spectrum of each galaxy to set the base level of the actual emission feature equal to the base level of the templates at zero intensity. Then, the peak intensity in the $H\alpha$ + $[NII]$ complex was measured from the continuum-subtracted spectrum. This value of the intensity was needed to re-normalize the template spectra.

An IRAF script was written to carry out the final steps of this deblending procedure in an automatic and uniform manner. To establish a starting point, the $H\alpha$ and $[NII]$ templates were each re-normalized to the peak intensity of the $H\alpha$ + $[NII]$ complex. Next, the templates were multiplied by a set of independent scaling factors (which ranged from 0.1 to 1.2), and then were summed to create a blended template (Figure 1). The difference was taken between the continuum-subtracted spectrum of the galaxy and the blended template, creating a residual spectrum. Finally, the script performed a statistical analysis on the region within the residual spectrum which spanned the wavelength range of the $H\alpha$ + $[NII]$ complex, and included approximately 200 Å of continuum on either side of this line. The root-mean-square (rms) of the deviations from the mean within the region was calculated during this step.

The script repeated this procedure iteratively for the range of scale factors between 0.10 and 1.20 in intervals of 0.02. The results of each iteration were written to an output file, sorting the output in order of increasing rms. The combination of

scale factors for which the rms was minimized was chosen as the best fit to the $H\alpha+[NII]$ complex. The best fits typically had values of the rms that were within $\pm 10\%$ of the rms in the galaxy continuum. Examples of the deblending are shown in Figure 2. Examples are shown having both high and low S/N, and with strong and weak $[NII]$.

Once the deblending was complete, the fluxes in the three components of the $H\alpha+[NII]$ complex were measured from the scaled images of the $H\alpha$ and $[NII]$ templates. The procedure for measuring these fluxes was the same as for the other lines in the spectrum.

Uncertainties due to the deblending process were estimated in the following manner. The $[NII]$ template was multiplied by the scale factor that resulted in the best fit to the $H\alpha+[NII]$ complex, while the $H\alpha$ template was multiplied by a range of scale factors surrounding its best fit value. For each iteration of this process, the magnitude of the residual between the actual line and the combined line templates was measured. All of the scale factors that produced residuals with magnitudes less than twice the rms in the continuum were recorded. The change in the flux of the $H\alpha$ template corresponding to this range of scale factors was defined as the uncertainty in the $H\alpha$ flux due to the deblending process. The uncertainty in the $[NII]$ lines were estimated in the same manner. These uncertainties were added in quadrature to the measurement uncertainties described in Section 5.6

5.3 Correction for Balmer Absorption

An important correction must be made to the measured fluxes of the Balmer emission lines to compensate for hydrogen absorption features in the underlying stellar continuum. Models of stellar atmospheres (Kurucz 1979) show that the equivalent widths for the $H\alpha$, $H\beta$ and $H\gamma$ absorption features are approximately equal within any given star. The $H\beta$ and $H\gamma$ equivalent widths agree within 3%.

This theoretical result is consistent with observation. In spectra of galaxies having sufficiently high resolution and signal-to-noise, the Balmer emission and absorption features can be measured simultaneously. Because of the dispersion of stellar velocities within a galaxy, the Balmer absorption features are generally broadened relative to the emission lines which are emitted from discrete regions, often near the galaxy's center. This difference in line widths allows for deconvolution of the two features, leading to separate measurements of their equivalent widths.

Keel (1983) found that both the $H\alpha$ and $H\beta$ absorption lines in the nuclei of bright spiral galaxies have equivalent widths of 1 - 3 Å. McCall et al. (1985) observed 99 extra-galactic HII regions in 20 galaxies, and found that the mean equivalent widths of the underlying Balmer absorption features were typically 1.9 Å.

These results have led many authors to correct the fluxes of Balmer emission lines in the spectra of galaxies by the addition of a constant based on a uniform estimate of the equivalent widths of the hydrogen absorption features. Kennicutt (1992, hereafter K92) adopted a value of $EW = 5 \text{ Å}$ to correct for underlying Balmer absorption in spectra of nearby ELGs. Contini et al. (1995) made a correction of

$EW = 2 \text{ \AA}$ for underlying absorption in the starburst galaxy Mrk 712. Liu & Kennicutt (1995) applied a correction of $EW = 4.7 \text{ \AA}$ for Balmer absorption in systems of merging galaxies.

PTP also made this type of correction to measurements of the emission lines from ten of the Bootes Void galaxies. They chose an equivalent width of $2 \text{ \AA}$ to compensate for the underlying Balmer absorption. Because these ten galaxies are included in our sample, we also adopted a correction of $EW = 2 \text{ \AA}$ to simplify comparisons between our observations and theirs. However, it is noted that this correction could be too small to correct for all the contamination due to underlying stellar populations.

5.4 Reddening Correction

All the fluxes in the emission lines were corrected for extinction by interstellar dust along the line-of-sight. This extinction is primarily caused by the scattering of photons by interstellar dust, although, some absorption of photons by the dust is also occurring (Savage & Mathis 1979). The interstellar extinction is wavelength-dependent because the dust scatters blue photons more efficiently than red. Thus, the interaction of light with interstellar dust is often referred to as reddening.

To correct the fluxes in emission lines for the effects of reddening, it is assumed that the properties of the dust everywhere along the line-of-sight are similar to the properties of the dust in the neighborhood of the Sun. This assumption is necessary because only the properties of the dust between the Sun and nearby stars

have been measured precisely enough to derive an accurate curve for the mean extinction as a function of wavelength. To correct these data, we used the average interstellar extinction curve of Savage & Mathis (1979), which was normalized to $H\beta$. This curve combines the interstellar extinction curves derived by several authors from data taken over a large range of wavelengths, including data from ultraviolet satellites.

The amount of reddening was derived for each galaxy observed according to

$$(2) \quad \text{Log}[I(\lambda)/I(H\beta)] = \text{Log}[F(\lambda)/F(H\beta)] + c[f(\lambda)-f(H\beta)]$$

where $I(\lambda)$ is the intrinsic flux at wavelength λ , $F(\lambda)$ is the observed flux, $f(\lambda)$ is the mean interstellar extinction normalized to $H\beta$, and c is the reddening parameter. The parameter c was evaluated using the observed flux ratios $H\alpha/H\beta$ and, when possible, $H\gamma/H\beta$ (corrected for underlying stellar absorption).

We used the intrinsic flux ratios $I(H\alpha)/I(H\beta) = 2.86$ & $I(H\gamma)/I(H\beta) = 0.468$ which were taken from the theoretical Balmer decrements of Hummer & Storey (1987), assuming Case B recombination with $T_e = 10^4$ K and $N_e \approx 10^2 \text{ cm}^{-3}$. These Balmer decrements were chosen to remain consistent with PTP, but they are nearly identical to the values $I(H\alpha)/I(H\beta) = 2.85$ & $I(H\gamma)/I(H\beta) = 0.469$ for $T_e = 10^4$ K and $N_e \approx 10^3 \text{ cm}^{-3}$, which have been used by many authors.

An exception was made for the AGNs in the sample. Theoretical and observational work by several authors (Ferland & Netzer 1983; Pequignot 1984; Gaskell & Ferland 1984; Binette 1985) has established an intrinsic $H\alpha/H\beta$

decrement of 3.10 for AGN's. This ratio of intensities arises from enhanced $H\alpha$ emission within a large, partly-ionized transition region where collisional excitation of hydrogen into the $n = 3$ level is significant. Thus, $I(H\alpha)/I(H\beta) = 3.10$ was used in the reddening correction of the known AGNs.

For galaxies with no $H\beta$ emission detected, no reddening correction could be performed. Thus, relative line fluxes reported for these galaxies in Table 1 have not been corrected for reddening. These galaxies include 1345+4641, 1407+4840, 1413+5056, 1428+5255, Mrk 845, 1517+3949 and 1540+5013.

The calculated values of the reddening parameter, c , are listed in Table 1 (col. 4). Mean values of c calculated from both the $H\alpha/H\beta$ ratio and the $H\gamma/H\beta$ ratio are denoted by a (*). In some cases, the values of c derived from both the $H\alpha/H\beta$ ratio and the $H\gamma/H\beta$ ratio are not in good agreement. The most probable explanation for this inconsistency is the low S/N in the $H\gamma$ line. For cases with extreme inconsistencies, only the value of c derived from the $H\alpha/H\beta$ ratio was used. In one case, the galaxy 1510+4727 was found to have a small, negative value of c . Therefore, this value of c was set equal to zero and no reddening correction was applied to this galaxy.

5.5 Continuum Shape, 41-50 Continuum Color & Stellar Absorption

In the absence of nuclear activity, the shape of the continuum emission from a galaxy (as a function of wavelength) is governed by the galaxy's stellar population. Therefore, examination of the continuum of a galaxy yields information

on its stellar composition and recent star formation history. As a qualitative analysis, we extracted the mean continuum shapes for the galaxies in our sample to look for trends (as a function of wavelength) that yield information on the stellar component of the galaxy.

The continua of our galaxies were fitted using the IRAF task CONTINUUM. Each combined galaxy spectrum was fitted using a third-order bicubic spline. Points more than 4σ below the fit were rejected to eliminate the effects of the two bad columns on the CCD, residuals from the subtraction of bright night-sky lines, and the increase in noise on the extreme blue end of the spectrum due to decreased sensitivity in the CCD. Points more than 3σ above the fit were rejected to eliminate the above effects, as well as the influence of any bright emission lines. Then a new fit was produced and outlying points were rejected again using the same criteria. This process was carried out for ten iterations to produce the best fit to the continuum.

This procedure produced a spectrum representing the mean continuum shape of each galaxy, which was then normalized to the flux at a reference wavelength of 5500 Å. The procedure also provided a measurement of the rms deviation from the mean representing the noise in the continuum. Examples of the continuum fitting are given in Figure 3. These examples include a continuum that increases toward the red, suggesting a population of predominantly cool stars; one that increases toward the blue, suggesting either a large number of hot, young O and B stars or blue non-thermal emission from an AGN; and one that shows significant stellar contributions at both ends of the wavelength range. A fourth galaxy (1432+5302) is included as

an example of an unusual continuum, with an extreme blue slope at short wavelengths similar to a B star. This continuum is discussed in more detail in Chapter 6.

None of the galaxy continua have been corrected for reddening. Also, in the discussion of the shapes of the galaxy continua in Chapter 6, the effects of reddening are not considered. In general, reddening will cause the observed continuum of a galaxy to increase more rapidly toward longer wavelengths than does the actual continuum. Thus, the galaxies in our sample which have continua that increase toward shorter wavelengths (and are not AGNs) have even more O and B stars than their continuum shapes would suggest.

More quantitative measurements of the shapes of the continua were also made using the "41-50" continuum color index defined by K92. This index compares the strength of the continuum emission at 4100 Å and 5000 Å, two wavelengths in a region sensitive to differences in stellar population. Mean continuum intensities were measured at rest wavelengths of 4050-4250 Å and 4900-5100 Å. The 41-50 color index is given by the expression

$$(3) \quad 41-50 \equiv 2.5 \text{ Log}[f_{\nu}(5000)/f_{\nu}(4100)]$$

where f_{ν} is the flux per unit frequency. The 41-50 colors for each galaxy in our sample are listed in Table 1 (col. 22). For comparison, the 41-50 colors of stars from each spectral type, from the library of stellar spectra compiled by Jacoby et al.

(1984), are also given in Table 4. The continuum colors are not corrected for reddening, which is consistent with K92.

TABLE 4. 41-50 Comparison Stars

Star	Spectral Type	41-50
HD 191978	O8.5	-0.31
HD 256413	B5	0.16
HD 240296	A6	0.08
BD+61 367	F5	0.34
BD+281885	G5	0.58
HD 21110	K4	1.44
SAO 62808	M5	1.61

Stellar absorption features have been identified in the spectra of many of the galaxies in the sample. This absorption is due to the presence of atoms and molecules in the atmospheres of the stars within the galaxies. The absorption lines include the Na D, Mg b and G band features.

The Na D feature corresponds to the pair of sodium lines at 5890 Å and 5896 Å. The absorption feature is roughly centered on these transitions and can be broadened by the thermal motions of the absorbing atoms. This feature has been used as an indicator of the number of older or higher-metallicity stars present in a galaxy (Worthey et al. 1994).

The magnesium triplet, Mg I b, centered at approximately $\lambda 5175$, is strong in the spectra of G and K stars. This line is often blended with a MgH line to form a blended feature (Guinan & Smith 1984) and is usually referred to as Mg b. The

detection of this line in a galaxy's spectrum is a good indication of the presence of late-type stars.

Fraunhofer's G band is a molecular absorption band of the CH molecule. The line is centered at approximately $\lambda 4304$. This feature is strongest in the spectra of late-type G, K & M stars.

The presence of Na D, Mg b and G band absorption features in the spectra of galaxies is a good indication of an underlying population of late-type stars. The absence of these lines in a continuum with good S/N implies a stellar population dominated by early-type stars. These absorption features, combined with the 41-50 color index and the continuum shape, are analyzed to constrain the stellar components of the Bootes Void galaxies.

5.6 Estimation of Uncertainties

The primary components of the noise in each galaxy spectrum are the readout noise and the "shot noise." The readout noise is the noise generated by the CCD output amplifier. The contribution of the readout noise in the spectrum is proportional to the number of pixels contained in the extraction aperture. The shot noise arises from Poisson variations in the number of counts measured per pixel, and is proportional to the square root of the number of electrons (photons) detected.

We use the rms deviation from the mean fit to the continuum (described in Section 5.5) as a measurement of the uncertainty in the continuum due to noise.

Then, the uncertainty in the flux of an emission line is calculated according to the expression (Gonzalez-Delgado et al. 1994)

$$(4) \quad \sigma_L = \sigma_{cont} N^{1/2} [1 + EW(N\Delta)^{-1}]^{1/2}$$

where σ_L is the uncertainty in the line flux, σ_{cont} is the uncertainty the continuum, N is the number of pixels used to measure the line, EW is the equivalent width of the measured line in $\text{\AA}$, and Δ is the dispersion in $\text{\AA}/\text{pixel}$.

Direct integration was used to measure the flux in each line, which is equivalent to measuring the area beneath the curve defined by the continuum and the line profile. This expression takes into account the uncertainties (due to noise) in measuring these two geometric components of the emission line. The first term is associated with the uncertainty in setting the base level of the line at the continuum. The second term scales the shot noise measured in the continuum to the level of the flux in the line, thus taking into account the uncertainty in measuring the profile (or "top") of the line.

This method for calculating the uncertainties assumes that the spectra are dominated by shot noise and that the readout noise is small. Because of the large slit heights used in the extraction of our spectra, the readout noise (which is proportional to the number of pixels sampled) was the dominant component of the noise. Thus, Eq. (4) scaled the shot noise *and* the readout noise up to the flux in the line, as if the rms in the continuum was only due to shot noise. By doing this, this method provides an overestimate of the uncertainty of the flux in each line. This

overestimate is acceptable for two reasons: (1) the strong emission lines have large S/N ratios (and small fractional uncertainties) even with the overestimate of σ_L , and (2) in the limit as the flux in the line approaches zero, σ_L approaches σ_{cont} . Therefore, the uncertainties in the weak lines are not greatly overestimated. The uncertainties in each measured line flux, estimated by this method, are reported in Table 1.

Next, a criterion is established for categorizing the detection of a line based on its associated uncertainty. This procedure provides a qualitative indication of the confidence warranted by various S/N ratios.

The ratio of the intensities of the [OIII] $\lambda\lambda 4959, 5007$ lines is known to be $\lambda 4959/\lambda 5007 = 0.33$ (K92). These emission lines are present in the spectra of many of the void galaxies with a broad range in EW. The S/N ratios of the weaker $\lambda 4959$ lines are plotted as a function of the difference between the measured $\lambda 4959/\lambda 5007$ ratios and the known ratio (Figure 4). For $S/N > 50$, the residuals vary by less than 0.03 (< 10%). Between $S/N = 25$ and $S/N = 50$, the mean of the residuals is 0.12 (> 36%). Below $S/N = 25$, the spread in the residuals balloons to encompass values from 0.04 to 0.59.

Even though these residuals contain components of the uncertainties of both lines, it is clear from this analysis that fluxes of lines with $S/N < 25$ should not be regarded with the same level of confidence as those lines having $S/N > 25$. Therefore, in the discussion of the emission lines observed in each galaxy, two classes of emission lines are defined: those having $S/N > 25$ and those with $S/N < 25$. These definitions are not part of the formal uncertainty calculation but do reflect

the level of confidence that should be placed in the subsequent analysis of the line intensities.

5.7 Classification of Emission Line Galaxies

One of the primary goals of this spectroscopic survey is to use line-intensity diagnostics to determine whether the ELGs in the void are HII region-like galaxies (also known as HII galaxies) or AGNs. HII galaxies have spectral emission features that are very similar to those observed in the HII regions in our own Galaxy. The spectra are similar because the emission features in the HII galaxy radiate from HII regions either within the disk of the galaxy or near its nucleus.

Baldwin et al. (1981) have shown that ELGs having different sources of photoionizing radiation can be distinguished from one another on two-dimensional plots of particular line-intensity ratios. Veilleux and Osterbrock (1987, hereafter VO87) proposed a similar method for classifying ELGs based on the ratios of lines commonly observed in the spectra of these galaxies: [OIII] λ 5007, [NII] λ 6583, [SII] $\lambda\lambda$ 6717,6731, [OI] λ 6300, H α & H β . From this set, line intensity-ratios that exhibited a sensitivity to the classification of the various types of ELGs were identified. These ratios were also chosen to be between lines of similar wavelength, minimizing the effects of reddening or of systematic errors in the reddening correction.

Four line-intensity ratios discussed by VO87 are used to classify the Bootes Void galaxies. The utility of each ratio is discussed below:

[OIII] $\lambda 5007/H\beta$ - The intensity of the [OIII] $\lambda 5007$ line in the spectrum of a galaxy is proportional to the volume of the gas containing the O^{++} ion. Because the presence of this ion suggests a relatively high ionization state, strong $\lambda 5007$ emission (relative to $H\beta$) indicates an abundant source of high-energy (UV) photons capable of ionizing O^+ . This source could either be the hard continuum spectrum of an AGN or a large concentration of O and B stars.

Although galaxies with [OIII] $\lambda 5007/H\beta > 3$ are typically high-ionization AGNs (VO87), the most energetic HII galaxies also satisfy this criterion. These HII galaxies have been called extreme starburst galaxies (ESB) by Allen et al. (1991), and they are thought to be the youngest examples of violent star formation episodes. Despite their strong $\lambda 5007$ lines, ESBs tend to have relatively weak [NII] emission.

The $\lambda 5007/H\beta$ ratio is particularly good for distinguishing LINERs (low-ionization nuclear emission-line region galaxies; Heckman 1980), which usually have [OIII] $\lambda 5007/H\beta < 3$, from Seyferts ([OIII] $\lambda 5007/H\beta \geq 3$).

[SII] $\lambda\lambda 6717,6731/H\alpha$ & [OI] $\lambda 6300/H\alpha$ - The [SII] $\lambda\lambda 6717,6731$ doublet and the [OI] $\lambda 6300$ line originate primarily in a thin, partly-ionized transition zone (cf. Section 5.4) produced by high-energy photons. This transition zone is not found in HII regions ionized by O and B stars (Osterbrock 1974). The size of this zone, and hence the strength of these lines, is proportional to the number of high-energy photons emitted from the source. Strong [SII] $\lambda\lambda 6717,6731$ and [OI] $\lambda 6300$ emission (relative to $H\alpha$) are reliable indications of a hard-photon source as found in AGNs.

[NII] $\lambda 6583/H\alpha$ - The presence of strong [NII] $\lambda 6583$ relative to $H\alpha$ is often observed in AGNs. The ratio of these lines in AGNs is generally $[NII] \lambda 6583/H\alpha \geq 0.7$ (VO87). This ratio suggests much stronger [NII] emission than the ratio $([NII]\lambda 6548 + \lambda 6583)/H\alpha \approx 0.33$ found in a sample of normal galaxies with $H\alpha$ emission (Kennicutt and Kent 1983, hereafter KK83). For this reason, [NII] $\lambda 6583/H\alpha$ is another useful diagnostic for separating the two classes of ELGs.

In order to classify the ELGs in the Bootes Void as HII galaxies or AGNs, we applied the line-intensity diagnostics of VO87 using the line ratios described above. The line fluxes used in this analysis were corrected for reddening and for the effects of underlying Balmer absorption as described in Sections 5.3 and 5.4. Diagrams of the line diagnostics are presented in Figures 5-7.

In each of these figures, the solid curve represents the boundary between HII galaxies and AGNs derived by VO87. Typically, HII galaxies lie on the left side of this curve and AGNs on the right. However, these diagnostics do not separate the two classes of emission line objects perfectly. A "transition zone" exists around the curve with a width of approximately ± 0.15 units on the horizontal axis. ELGs of both types are found to lie within this transition zone. VO87 find that the diagram with $\lambda 5007/H\beta$ plotted as a function of $[OI] \lambda 6300/H\alpha$ (Figure 7) is the most useful diagnostic for distinguishing AGNs from HII galaxies.

Classifications of the void galaxies using these diagnostics are included in the description of the individual galaxies in Chapter 6. The broader implications of these results are discussed in Chapter 9.

5.8 Galaxy Redshifts

In order to examine the accuracy of the wavelength calibration and the methods of line measurement, the redshifts for the void galaxies measured from these spectra are compared to the redshifts published by other authors (see C97 for references). Redshifts were determined using all of the detected emission and absorption features.

The redshift data for the sample are given in Table 5. We did not observe the galaxy 1519+5050 (CG 693), so it is not included. Columns (1) & (2) are the same as those in Table 1. Column (3) lists the references from which the published redshifts were taken (see the notes on Table 1 for references). Published values for the redshifts are listed in column (4). The mean redshifts measured for each galaxy are given in column (5). The uncertainties listed in column (6) are simply the standard deviation about the mean. The difference between the measured and published redshifts are listed in column (7). The root-mean-square of the differences is 0.0007. In Figure 8, the measured redshifts are plotted against the published redshifts. A linear least-squares fit was performed to derive the best-fit line for the data. The slope of this line is 0.964 and the y-intercept is 0.0015. These results indicate good agreement between the redshifts measured from our spectra and those previously published.

Table 5. Redshift Data for the Bootes Void Galaxies

Galaxy (1)	ID (2)	Ref. (3)	Published z (4)	Mean z (5)	σ_z (6)	Difference (7)
1345+4641		8	0.052	0.05159	0.0007	***
1357+4641		8	0.054	0.05318	0.0005	***
1406+4905	I Zw 81	3	0.05156	0.05180	0.0004	0.0024
1407+4840	CG 910	5	0.04336	0.04343	0.0009	0.0007
1408+4852	CG 370	6	0.0444	0.04474	0.0004	0.0003
1413+5056		7	0.04922	0.05007	0.0010	0.0008
1428+5255		5	0.04448	0.04545	0.0006	0.0010
1432+5302	CG 474	4	0.0446	0.04494	0.0005	0.0003
1444+4402	CG 538	7	0.04324	0.04307	0.0005	-0.0002
1446+4457	CG 547	4	0.0432	0.04316	0.0005	-0.00004
1457+4228	CG 598	2	0.05743	0.05777	0.0001	0.0003
1458+4944	CG 922	9	0.0475	0.04834	0.0010	0.0008
1503+5428	CG 620	9	0.0478			
1505+3958	CG 629	6	0.0518	0.05203	0.0008	0.0002
1506+5138	Mrk 845	3	0.04542	0.04461	0.0010	-0.0008
1507+4554	CG 642	3	0.04837	0.04867	0.0010	0.0003
1510+4727	CG 657	4	0.0527	0.05301	0.0012	0.0003
1517+3949		10	0.0474	0.04711	0.0007	-0.0003
1517+3956	CG 684	2	0.04701	0.04729	0.0006	0.0003
1519+5050	CG 692	11	0.0566	0.05579	0.0007	-0.0008
1530+4332	Main	7	0.05164	0.05287	0.0004	0.0012
1530+4332	Comp.	7	0.05164	0.05110	0.0009	-0.0005
1535+3831		7	0.05078			
1537+5315		7	0.05196			
1540+5013		7	0.05427	0.05592	0.0005	0.0017
1547+5121		5	0.04985	0.05074	0.0007	0.0009

*** - Differences not calculated for these galaxies because the redshifts were measured from the same spectra.

CHAPTER 6

DESCRIPTION OF INDIVIDUAL GALAXIES

In this chapter, the individual galaxy spectra are discussed. All of the emission and absorption features detected in the combined spectrum of each galaxy and listed in Table 1 are described below. Emission lines with signal-to-noise ratios (S/N) greater than 25 are referred to as prominent lines. Emission lines with $S/N < 25$ are referred to as having *low S/N* (cf. Section 5.6).

For Table 1, the galaxy designation used by C97 is listed in column (1). Column (2) gives alternate identifications for the sample. Column (3) identifies the discovery paper for each galaxy. The reddening correction parameters, c , are listed in column 4. Columns (5)-(17) are the fluxes of emission lines normalized to the flux at the reference wavelength of 5500 Å. Normalized fluxes are reported instead of absolute fluxes due to the non-photometric observing conditions under which some of the data were taken. Column (18) shows the equivalent width of the $H\alpha+[NII]$ complex in Å. These values are negative because they represent emission lines. Equivalent width is defined to be positive for absorption features. Columns (19)-(21) are the equivalent widths of stellar absorption features in Å. The 41-50 continuum color index is reported in column (22). Column (23) lists the mean flux

near 5500 Å in units of 10^{-15} ergs cm⁻² s⁻¹ Å⁻¹. These values are used only as normalization parameters.

The general shapes of the galaxy continua are examined below in order to identify trends in the underlying stellar population. Because this analysis is admittedly qualitative, the 41-50 spectral color indices are also discussed to aid in quantifying continuum shapes (cf. Section 5.5). These data are compared to the broadband (B-V, V-R and R-I) color indices measured by C97 to check for consistency.

KK83 have shown a correlation between the flux in the H α + [NII] complex and the star formation rate within a galaxy. They find that among normal galaxies with H α emission, the $EW(H\alpha+[NII]) \leq 50$ Å. The average $EW(H\alpha+[NII])$ for their sample is ~ 19 Å. K92 states that among galaxies with normal star formation rates, the $EW(H\alpha+[NII]) \leq 40$ Å. These values of $EW(H\alpha+[NII])$ are used as references with which to compare the flux in H α + [NII] from the void galaxies.

Ratios of emission lines are used to determine the physical properties of the ionization source within each galaxy. The line-intensity diagnostics discussed in Section 5.7 are applied to all of the galaxies from which the appropriate emission lines were detected. Diagrams of the line-intensity diagnostics, similar to those used by VO87, are presented in Figures 5-7. For the subset of our sample also observed by PTP, changes in the locations of galaxies on these diagrams due to differences in the line ratios between the two studies are discussed.

1345+4641: The $H\alpha$ emission line is prominent in this galaxy, along with a low S/N [SII] $\lambda\lambda 6717, 6731$ line (Figure 9). A weak feature is present near the expected position of $H\beta$; however, the redshift calculated from this line does not agree with the other two emission lines and it is not considered a detection. For this galaxy, $EW(H\alpha) = 37 \text{ \AA}$, which is within the range of galaxies with normal star formation rates (K92).

The continuum of this galaxy rises sharply toward the blue between $4500 \text{ \AA}$ and $5500 \text{ \AA}$, and is mostly flat between $5500 \text{ \AA}$ and $7500 \text{ \AA}$. This shape is consistent with the small (blue) value of the broadband color $V-R = 0.30 \pm 0.12$, but seems inconsistent with the large (red) value of $B-V = 0.79 \pm 0.13$ (C97). Unfortunately, the spectrum provided to us by SSG (private communication) does not sample wavelengths shorter than $4500 \text{ \AA}$, which is necessary to provide adequate coverage of the B filter. The continuum shape certainly suggests an excess of blue stars, indicating a recent episode of star formation.

1357+4641: The prominent emission lines detected in the spectrum of this galaxy (also provided to us by SSG) are $H\alpha$ and [OIII] $\lambda 5007$ (Figure 10). Also, low S/N $H\beta$, [SII] $\lambda\lambda 6717, 6731$ and [OIII] $\lambda 4959$ are detected. The $EW(H\alpha + [NII]) = 44 \text{ \AA}$, which is near the upper limit for galaxies with normal star formation rates (K92). Using line-intensity diagnostics, 1357+4641 is classified as an HII galaxy (Figure 5).

The continuum of this galaxy is nearly flat between $6000 \text{ \AA}$ and $7000 \text{ \AA}$, increases slightly to the red from $5300 \text{ \AA}$ to $6000 \text{ \AA}$, and increases toward the blue at wavelengths shorter than $5300 \text{ \AA}$. This continuum shape seems inconsistent with the

broadband colors ($B-V = 0.99 \pm 0.21$; $V-R = 0.50 \pm 0.10$) measured by C97. However, the continuum does reflect an excess of blue stars, which is compatible with the $H\alpha$ and [OIII] emission. These data suggest that this galaxy has experienced a recent episode of star formation.

1406+4905 (CG 359): This galaxy is I Zw 81. Based on line-intensity diagnostics, VO87 classify this galaxy as a "narrow-line AGN" and PTP find it to be a LINER. In our spectra, we detect a strong $H\alpha$ + [NII] emission feature and prominent [OIII] $\lambda 5007$ and [SII] $\lambda\lambda 6717, 6731$ emission lines (Figure 11). Low S/N $H\beta$ and [OIII] $\lambda 4959$ lines are also detected. In addition, the G band and Mg b stellar absorption features are observed in the spectrum, suggesting the presence of an older, metal-rich stellar population.

The presence of a significant older stellar population is consistent with the continuum shape of this galaxy, which increases strongly toward the red from 4000 Å to 5000 Å, and gradually toward the red at wavelengths longer than 5000 Å. This general continuum shape is also consistent with the moderately-red broadband colors (C97). Any blue non-thermal emission from an AGN is not strongly affecting the blue continuum of this galaxy.

Deblending of the $H\alpha$ + [NII] complex reveals the presence of relatively strong [NII] $\lambda\lambda 6548, 6583$ lines, with a [NII]/ $H\alpha$ ratio of 0.87. This ratio is large compared to the average ratio in ELGs observed by K92. The enhanced [NII] emission is consistent with this galaxy being an AGN. Line-intensity ratios involving $\lambda 6583$ place this galaxy in the AGN region of Figure 6, although near the

transition zone. In Figure 5, however, this galaxy falls in the region of the HII galaxies. Using a diagram similar to Figure 5, PTP classify this galaxy as an AGN. This difference might be due to the larger slit through which our spectra were taken. A larger slit would include more Balmer emission from outside the nucleus (if present), causing a variation in line-intensity ratios from a purely nuclear spectrum. Increased $H\alpha$ emission from outside the nucleus would push the galaxy to the left in Figure 5, moving it onto the side of the HII galaxies.

1407+4840 (CG 910): The prominent emission features in this galaxy are $H\alpha$ + $[NII]$ and $[SII] \lambda\lambda 6717, 6731$ (Figure 12). No other emission features are detected. Stellar absorption bands of Na D, Mg b and G band are also present. The $EW(H\alpha+[NII]) = 34 \text{ \AA}$, which is within the range of galaxies with normal star formation rates (K92). Sage et al. (1997) find an unusual distribution of CO emission in this galaxy, suggesting the possibility of tidal interaction. However, imaging of this galaxy shows no evidence of such an interaction (C97).

The continuum of 1407+4840 increases gradually toward redder wavelengths, consistent with the moderately-red broadband colors. The 41-50 color index is 0.64 which is red compared to the sample average. These data suggest that the continuum of this galaxy is dominated by mid- to late-type stars, which is consistent with the presence of the stellar absorption features.

1408+4852 (CG 370): This galaxy is a disturbed system with a tidal tail (C97). Spectra of this galaxy show several prominent emission features including $H\alpha$, $H\beta$,

[OIII] $\lambda\lambda 4959, 5007$ and [SII] $\lambda\lambda 6717, 6731$ (Figure 13). Lines of H γ , HeI $\lambda 5876$ and [OI] $\lambda\lambda 6300, 6364$ are also detected with low S/N. The detection of $\lambda 5876$ might indicate the presence of Wolf-Rayet stars (very young O stars with strong stellar winds) within this galaxy. The $\lambda 5876$ line is formed within the wind/chromosphere complex of these stars (Catala et al. 1993). The presence of Wolf-Rayet stars is a strong indication of a very recent episode of star formation.

Deblending of the H α line was attempted, but the [NII] emission suggested by the process was negligible. This is consistent with the relatively weak $\lambda 6583$ emission observed by PTP. Even with the apparent paucity of [NII] emission, the $EW(H\alpha + [NII]) = 74 \text{ \AA}$, suggesting a high rate of star formation (K92).

The presence of the [OI] lines requires an abundance of high-energy photons, emitted from either an active nucleus or many O and B stars. Although the $\lambda 6300$ line is very low S/N in our spectra of this galaxy, we plot its intensity ratio with H α in Figure 7. This line-intensity diagnostic indicates that 1408+4852 is an HII galaxy and not an AGN. This result is consistent with the galaxy's location in Figure 5. Thus, we classify this galaxy as an HII galaxy, in agreement with the interpretation of PTP.

The continuum of this galaxy increases toward the blue and has a blue 41-50 color index of 0.18. These data are consistent with its blue broadband colors (C97). 1408+4852 appears to have a large population of blue stars which were probably formed in a recent episode of star formation triggered by tidal interaction.

1413+5056: This galaxy has a double nucleus (C97). The only prominent emission feature detected in this galaxy is $H\alpha$, with $EW(H\alpha) = 12 \text{ \AA}$ (Figure 14). The [SII] $\lambda\lambda 6717, 6731$ blend is also detected with low S/N. The $H\beta$ line is present in absorption, along with the Mg b and G band stellar absorption features. The continuum of this galaxy shows an increase toward the red consistent with its broadband colors (C97). The color index is $41-50 = 0.72$, which is red compared to the sample average. These data would suggest that 1413+5056 has an average stellar population with a modest rate of star formation among galaxies with $H\alpha$ emission. This would appear to be inconsistent with the galaxy's unusual morphology. However, Kennicutt et al. (1987) have noted that starburst episodes triggered by tidal interactions are not long-lived. This galaxy might be a post-starburst system, although higher S/N spectra would be needed to determine this.

1428+5255: This galaxy has been classified as a Seyfert 2 by Moran et al. (1994). The $H\alpha+[NII]$ emission feature is the only prominent line in our spectrum of this galaxy, with $EW(H\alpha+[NII]) = 21 \text{ \AA}$ (Figure 15). The [SII] $\lambda\lambda 6717, 6731$ and [OIII] $\lambda\lambda 4959, 5007$ lines are also detected, but with low S/N. The Na D, Mg b and G band stellar absorption features are also detected. $H\beta$ may be present in absorption.

The continuum of this galaxy increases strongly toward the red, with a red 41-50 color index of 0.76. This continuum shape is consistent with its red broadband colors (C97). This galaxy appears to have a standard stellar population with a predominance of older, metal-rich stars. No contribution to the blue continuum due to non-thermal emission from the AGN is detected.

The spectrum of 1428+5255 published by Moran et al. (1994) was taken on a 2-meter class telescope. Their spectrum is very similar to ours, having similar emission line-intensities with the same absorption features and general continuum shape. The only difference is they detect a weak H β emission feature which we do not. It is possible that we included more of the stellar component of the galaxy in our spectrum, resulting in greater Balmer absorption which might have offset any H β emission. The similarity of these spectra supports the accuracy of our data set, in general.

1432+5302 (CG 474): This galaxy has many prominent emission lines including H α + [NII], H β , H γ , [OIII] $\lambda\lambda$ 4959, 5007 and [SII] $\lambda\lambda$ 6717, 6731 (Figure 16). Other lines were detected with low S/N; [OI] $\lambda\lambda$ 6300, 6364, HeI λ 5876 (possibly from Wolf-Rayet stars), [OIII] λ 4363 and H δ . The $EW(H\alpha+[NII]) = 207 \text{ \AA}$, which is very large even compared to a sample of ultra-luminous IRAS mergers (Liu et al. 1995). Using the ratio of intensities of the [OIII] lines (λ 4959+ λ 5007)/ λ 4363, and assuming an electron density of $N_e = 10^3$, we estimate an approximate nebular temperature of $1.3 \times 10^4 \text{ K}$. This temperature falls within the typical range for HII regions, which is $\sim 10^4 \text{ K}$.

Despite having a λ 5007/H β > 3 , this galaxy has $[NII]/H\alpha \approx 0.15$, which is more than a factor of 3 lower than the mean value in galaxies with H α emission (K92). Because of these line ratios, its large $EW(H\alpha+[NII])$ and its location on the line-intensity diagrams, Figures 5-7, we classify this galaxy as an ESB galaxy. The data of PTP are in good agreement with ours, suggesting that most of the emission

is in the nucleus of this galaxy. This assertion is consistent with $H\alpha$ imaging of this galaxy by Weistrop et al. (1995, hereafter W95), which shows strong emission concentrated in the nucleus.

The continuum of 1432+5302 has a strong increase toward the blue at wavelengths shorter than $\sim 5200 \text{ \AA}$, consistent with the blue broadband colors measured by C97. The blue end of this continuum is very similar in shape to a B star. There is also an increase in the continuum toward the extreme red end of the spectrum ($> 6800 \text{ \AA}$). This feature in the continuum confirms the presence of either an older stellar population or a large number of young, red supergiants. The 41-50 color index is -0.03, which is in agreement with the very blue broadband colors of this galaxy (C97). The colors of this galaxy, combined with the strength and distribution of the emission features, is indicative of a strong nuclear starburst.

1444+4402 (CG 538): The prominent emission features in this galaxy are $H\alpha + [NII]$ and $[SII] \lambda\lambda 6717, 6731$. $H\beta$ and weak $[OIII] \lambda\lambda 4959, 5007$ lines are detected with low S/N (Figure 17). The G band absorption feature is also detected. The $EW(H\alpha + [NII]) = 50 \text{ \AA}$, which is near the upper limit for galaxies with normal star formations rates (K92). Because of the weak $\lambda 5007$ emission, this galaxy lies in the region of the least energetic HII galaxies in Figures 5 & 6.

The continuum of this galaxy is mostly flat between $5000 \text{ \AA}$ and $7000 \text{ \AA}$, and the 41-50 color index is 0.43. These data are in agreement with the moderate broadband colors measured by C97. The continuum does not suggest an overabundance of O and B stars within this galaxy. The decrease in the continuum

short of 4500 Å, and the presence of G band absorption are consistent with an older stellar population.

1446+4457 (CG 547): This is a disk galaxy with the nucleus located off-center (C97). The prominent emission features include H α + [NII], H β , [OIII] $\lambda\lambda$ 4959, 5007 and [SII] $\lambda\lambda$ 6717, 6731 (Figure 18). Other features were detected with low S/N: H γ , HeI λ 5876 (possibly from Wolf-Rayet stars) and [OI] $\lambda\lambda$ 6300, 6364. The Mg b stellar absorption band was also detected. The EW(H α + [NII]) = 45 Å, which is near the upper limit for galaxies with normal star formation rates (K92).

The line-intensity ratios for this galaxy place it in the transition zone in Figure 5, but clearly in the region of HII galaxies in Figures 6 & 7; therefore, we classify it as an HII galaxy. It is noted that the λ 5007/H β ratio is significantly greater than that measured by PTP. This discrepancy might be due to our larger slit including more stars, which would increase the role of H β absorption on the λ 5007/H β ratio. This difference, however, does not change the conclusion that this is an HII galaxy.

The continuum of this galaxy increases toward the blue between 4000 Å and 6000 Å, indicating the presence of a significant fraction of blue stars. The spectrum > 7000 Å increases to the red. Given that the Mg b absorption line is present, this continuum feature implies a population of cool stars. These cool, red stars could either be part of an older stellar population or a portion of the young stars which have evolved off the main sequence to become red supergiants. The 41-50 color

index for this galaxy is 0.28. These data are in agreement with the moderately-blue broadband colors measured by C97.

1457+4228 (CG 598): Many of the characteristics of this galaxy are similar to 1446+4457. The morphologies of these galaxy appear remarkably similar, each having a bright nucleus located off-center in a surrounding disk (C97). Prominent emission lines observed in 1457+4228 include $H\alpha$ + $[NII]$, $H\beta$, $[OIII] \lambda 5007$ and $[SII] \lambda\lambda 6717, 6731$ (Figure 19). $[OIII] \lambda 4959$ is detected with low S/N. A dip in the continuum near $4550 \text{ \AA}$ might be the G band absorption feature blended with $H\gamma$ in absorption. The $EW(H\alpha+[NII]) = 79 \text{ \AA}$, which implies a high rate of star formation compared to normal galaxies with $H\alpha$ emission (K92).

Based on line-intensity ratios (Figures 5 & 6), we classify this galaxy as an HII galaxy, in agreement with PTP. However, as with 1446+4457, our $\lambda 5007/H\beta$ ratio is greater than that measured by PTP. The same explanation for this discrepancy that was proposed for 1446+4457 is offered here. The shape of the continuum of 1457+4228 is also similar to 1446+4457, suggesting a slight excess in the fraction of blue stars and a measurable contribution from cool, red stars. The 41-50 color index is 0.24, which is in agreement with the moderately-blue broadband colors measured by C97.

1458+4944 (CG 922): The prominent emission lines in this galaxy consist of $H\alpha$ + $[NII]$, $H\beta$, $[OIII] \lambda\lambda 4959, 5007$ and $[SII] \lambda\lambda 6717, 6731$ (Figure 20). A low S/N

H γ line, and a G band absorption feature are also observed. The H α + [NII] feature is very strong relative to the continuum, with $EW(H\alpha+[NII]) = 127 \text{ \AA}$.

The emission from forbidden lines is strong in 1458+4944, and line-intensity diagnostics place this galaxy within the AGN region in both Figures 5 & 6. In Figure 6, however, the galaxy falls close to the dividing line between HII galaxies and AGNs.

The continuum of this galaxy clearly increases toward the blue, and the 41-50 color index is 0.16. These properties are consistent with the blue broadband colors reported by C97. This galaxy was unresolved in broadband imaging, yet it is relatively bright ($M_r = -19.84 \pm 0.07$) compared to the other unresolved galaxies in the Bootes Void sample (C97). This morphology is suggestive of nuclear emission.

Considering all of these data, we classify 1458+4944 as an AGN. Because it has $\lambda 5007/H\beta < 3$, this galaxy is most likely a LINER (VO87). This galaxy has not previously been classified as an AGN.

1503+5428 (CG 620): No emission lines are detected from this galaxy (Figure 21). The mean flux from the continuum is $1.33 \times 10^{-16} \text{ ergs/cm}^2/\text{sec}/\text{\AA}$. The weakest lines in other galaxies in our sample that we have considered detections have $EW > 1 \text{ \AA}$. If we consider this $EW = 1 \text{ \AA}$ as an approximate detection limit, then the H α + [NII] flux from 1503+5428 must be less than $1.33 \times 10^{-16} \text{ ergs/cm}^2/\text{sec}/\text{\AA}$. However, spectra of this galaxy were not taken under photometric conditions, and this flux limit is only an estimate, at best. The continuum of this galaxy increases toward the red, which is consistent with the red broadband colors measured by C97.

1505+3958 (CG 629): This galaxy has prominent emission lines of $H\alpha+[NII]$ and $[SII] \lambda\lambda 6717, 6731$ (Figure 22). The low S/N lines $H\beta$ and $[OIII] \lambda\lambda 4959, 5007$ were also detected, along with the Mg b absorption feature. The $EW(H\alpha+[NII]) = 30 \text{ \AA}$, which is within the range of galaxies with normal star formation rates (K92).

The analysis of the line-intensity diagnostics for this galaxy is not straightforward. In Figure 5, this galaxy falls in the region occupied by AGNs. In contrast, PTP measure line intensities that place this galaxy in the transition zone very near the dividing line between AGNs and HII galaxies. Most notably, the $\lambda 5007/H\beta$ ratio from our spectra is a factor of 3 greater than that reported by PTP. The S/N in both sets of measurements is low, and this discrepancy is probably the result of measurement uncertainty.

In Figure 6, 1505+3958 falls along the dividing line between AGNs and HII galaxies. The galaxy's location on this diagram is also significantly different than is suggested by the line-intensities of PTP, which place the galaxy well within the area occupied by HII galaxies. Considering all the data, the evidence is certainly not strong enough to classify this galaxy as an AGN; therefore, it is categorized as an HII galaxy.

The continuum of this galaxy has a gradual increase toward the blue between 4500 $\text{\AA}$ and 6500 $\text{\AA}$. The 41-50 color index is 0.34, the same as that of an F star. The shape of the continuum is not consistent with the broadband colors measured by C97 ($B-V = 0.79 \pm 0.07$; $V-R = 0.30 \pm 0.04$). These colors indicate excess flux in the V filter (centered at approximately 5300 $\text{\AA}$) compared to the B filter (centered at approximately 4200 $\text{\AA}$). Neither the $H\beta$ line nor the $[OIII] \lambda\lambda 4959, 5007$ lines have

sufficient flux to affect the broadband colors in such a manner. C97 report a blue region south-east of the nucleus, which would have fallen within our slit. This region might have contributed to the blue continuum short of 5300 Å and yet have been small enough to have no significant affect on the integrated broadband colors.

1506+5138 (CG 636): This galaxy is Mrk 845. Osterbrock and Dahari (1983) have classified it as a Seyfert 1 galaxy. However, in our spectra, the flux from the stellar continuum is apparently dominating the emission lines. The only prominent emission feature is the H α + [NII] complex (Figure 23). Low S/N [OIII] $\lambda\lambda$ 4959, 5007 lines are also present, but no H β is detected. The Mg b and G band stellar absorption features are detected. The continuum of this galaxy is nearly flat between 5000 Å and 7000 Å, with a downward slope at shorter wavelengths. The 41-50 color index for this galaxy is 0.62, which is consistent with the red broadband colors measured by C97. We do not detect a strong contribution to the continuum due to blue non-thermal emission from the AGN. This galaxy does have a very bright, circular nucleus (C97) consistent with its classification as an AGN.

1507+4554 (CG 642): This galaxy has more prominent emission lines than any other galaxy in our sample, except 1510+4727. These lines include H α + [NII], H β , H γ , H δ , [OIII] $\lambda\lambda$ 4959, 5007 and [SII] $\lambda\lambda$ 6717, 6731 (Figure 24). Low S/N lines of He and HeI λ 5876 (possibly from Wolf-Rayet stars) were also detected, and possibly [OII] λ 3727 at the extreme blue end of the spectrum. (Data at the extreme blue end of these spectra are unreliable due to decreased sensitivity of the CCD.) The

$H\alpha+[NII]$ complex is remarkably strong with respect to the continuum, having an $EW(H\alpha+[NII]) = 455 \text{ \AA}$.

Line-intensity diagnostics place this galaxy in the regions occupied by high-excitation, HII galaxies in Figures 5 & 6. This result agrees with the analysis of PTP. Because this galaxy is not an AGN, the substantial $EW(H\alpha+[NII])$ implies an enormous rate of star formation (K92). Also, this galaxy has $\lambda 5007/H\beta > 3$, and $[NII]/H\alpha \approx 0.09$. For these reasons, we classify 1507+4554 as an ESB galaxy.

The large relative strengths of the emission lines with respect to the continuum are the most likely causes of the anomalous broadband colors measured by C97 ($B-V = 0.92 \pm 0.09$; $V-I = -0.02 \pm 0.14$). These colors indicate excess flux in the V filter centered at approximately $5300 \text{ \AA}$. The $H\beta$ and $[OIII] \lambda\lambda 4959, 5007$ lines lie near the center of this bandpass, and they have a combined EW equal to $246 \text{ \AA}$ of continuum.

The continuum increases at wavelengths shorter than $5000 \text{ \AA}$. The 41-50 color index is quite blue at -0.12 , very nearly that of a B star (-0.16), providing further evidence that the broadband colors of this galaxy are dominated by the emission features. The blue continuum color indicates a stellar population with an excess of O and B stars. These data also imply recent and violent star formation activity occurring within this galaxy.

1510+4727 (CG 657): This system is a merging or closely interacting galaxy pair (see Chapter 7). The spectrum discussed here was taken on a run prior to those used in the analysis in Chapter 7. The slit was aligned with the geometric center of the

system. The resulting spectrum must contain emission from each half of the galaxy. The redshift measured from this spectrum is intermediate to those discussed in Chapter 7, although more nearly in agreement with the southern nucleus. This spectrum is used for the analysis of the emission lines because it was taken on a photometric night, and the spectra used in Chapter 7 were not.

Prominent emission features in this system include $H\alpha+[NII]$, $H\beta$, $H\gamma$, $H\delta$, $[OIII] \lambda\lambda 4959, 5007$ and $[SII] \lambda\lambda 6717, 6731$ (Figure 25). Low S/N lines of $HeI \lambda 5876$ (possibly from Wolf-Rayet stars) and $[OI] \lambda\lambda 6300, 6364$ were also detected, and possibly $[OII] \lambda 3727$ at the extreme blue end of the spectrum. The $EW(H\alpha+[NII]) = 407 \text{ \AA}$, which is extremely large compared to normal galaxies with $H\alpha$ emission (K92).

Analysis of the line-intensity ratios for 1510+4727 yield curious results. In Figure 5, the $[SII]$ lines are relatively weak with respect to $H\alpha$. However, because of a very large $\lambda 5007/H\beta$ ratio, this system falls in the region of the diagram near the ESB galaxies. In Figure 6, significant $[NII]$ emission relative to $H\alpha$ causes this system to lie among the AGNs. The line-intensities reported by PTP make this difference in classification even more pronounced, placing this system farther to the left in Figure 5 and farther to the right in Figure 6. However, neither of these sets of observations are in agreement with Weistrop & Downes (1988), who classify this galaxy as an HII galaxy based on the line ratios used for Figure 6.

Finally, a sufficient flux is measured in the $[OI] \lambda 6300$ line to place this galaxy among the AGNs in Figure 7. Because of the manner in which $[OI]$ emission is produced in nebulae, VO87 define the line-intensity diagnostic involving $[OI]$ to

be the most sensitive discriminator between HII galaxies and AGNs. However, the S/N of the $\lambda 6300$ line in this spectrum is low, making accurate measurement difficult.

The continuum emission from 1510+4727 increases strongly toward the blue over the entire spectrum, which is consistent with its blue broadband colors (C97). The 41-50 color index is also quite blue at -0.12, very nearly that of a B star (-0.16). The blue continuum shape of this system certainly suggests a large fraction of blue stars. Blue non-thermal emission from an internal AGN may also be contributing to the continuum.

PTP classify 1510+4727 as an HII galaxy, but they were unaware of the possibility of this system being a merger. Tidal interaction may have stimulated nuclear activity which is responsible for the [OI] lines and the excess [NII] emission (Lin et al. 1988). Higher resolution spectra of each half of this system are needed to determine whether or not it contains an AGN.

1517+3949: This galaxy was first identified in an HI survey and its published redshift was determined from the 21-cm line (Szomoru et al. 1993). For the first time, we have identified optical emission lines in the spectrum of this galaxy at a redshift compatible with the HI data (Figure 26). The only prominent emission line is $H\alpha + [NII]$, with an $EW(H\alpha + [NII]) = 25 \text{ \AA}$. The [OIII] $\lambda\lambda 4959, 5007$ and [SII] $\lambda\lambda 6717, 6731$ lines are also present with low S/N. The Mg b and G band stellar absorption features are also detected.

The continuum of 1517+3949 has a gradual increase toward the blue and a moderately blue 41-50 color index of 0.39, which are consistent with its broadband colors (C97). These data indicate an appreciable fraction of hot stars combined with the population of cool stars suggested by the stellar absorption bands. Although Szomoru et al. (1993) report this galaxy to be associated with the active star-forming system 1517+3956, the $EW(H\alpha+[NII])$ would not suggest abnormally high star formation due to tidal interaction.

1517+3956 (CG 684): This system is a merging or closely interacting galaxy pair (see Chapter 7). The spectrum discussed here is of the southern half of the system because only one exposure of the northern half was taken. Prominent emission features include $H\alpha+[NII]$, $H\beta$, $H\gamma$, $[OIII] \lambda\lambda 4959, 5007$ and $[SII] \lambda\lambda 6717, 6731$ (Figure 27). Low S/N $HeI \lambda 5876$ (possibly from Wolf-Rayet stars) and $[OI] \lambda\lambda 6300, 6364$ lines, along with G band and Mg b stellar absorption bands, are also detected. The $EW(H\alpha+[NII]) = 154 \text{ \AA}$, indicating strong star formation. Based on line-intensity ratios (Figures 5 & 6), we classify this galaxy as an HII galaxy, in agreement with PTP. Bottinelli et al. (1989) report an OH megamaser within this system suggesting violent star formation activity.

The continuum increases toward the blue between 4500 $\text{\AA}$ and 6500 $\text{\AA}$. However, at wavelengths longer than 6800 $\text{\AA}$, the spectrum increases toward the red. These continuum features indicate an excess of hot O and B stars combined with a population of cool stars, consistent with the presence of G band and Mg b absorption. The 41-50 color index for 1517+3956 is 0.25, consistent with its blue

broadband colors (C97). This galaxy appears to be undergoing active star formation triggered by tidal interaction or merger.

1519+5050 (CG 692/693): This is a pair of interacting spiral galaxies. The larger (NW) galaxy, CG 692, has a single, extended spiral arm distorted by the tidal interaction (Weistrop et al. 1992, hereafter W92; and W95). Spectra of this pair taken on the Multiple Mirror Telescope are discussed by W92. Using these spectra, W92 classified CG 692 as an HII galaxy with widespread star formation, and CG 693 as a Seyfert 1. We have taken spectra of CG 692 which include a section of the single spiral arm and a region of strong H α emission. No new spectra of CG 693 were taken.

Prominent emission lines from the sampled region of CG 692 include H α + [NII], H β , [OIII] $\lambda\lambda$ 4959, 5007 and [SII] $\lambda\lambda$ 6717, 6731 (Figure 28). The H γ line is present with low S/N. The EW(H α + [NII]) $\approx$ 132 Å, indicating a significant amount of star formation compared to normal galaxies with H α emission (K92). Based on line-intensity ratios (Figures 5 & 6), we classify this galaxy as an HII galaxy, in agreement with W92.

The continuum of this galaxy increases strongly toward the blue, which is similar to spectrum of W92. The 41-50 color index is 0.14, which is consistent with the blue broadband colors of this galaxy (C97). All of these data suggest recent star formation activity and a large fraction of young blue stars. This interpretation is consistent with that of W92 and W95.

1530+4332: This is a galaxy pair separated by ~ 22 kpc ($20''$). The larger galaxy in the pair is located directly west of the smaller, allowing them to be placed along the slit together. Individual, one-dimensional spectra were extracted for each galaxy from the two-dimensional images. The larger galaxy to the west will be referred to as the main galaxy, with the smaller companion galaxy to the east (see C97).

The prominent emission lines in the main galaxy are $H\alpha+[NII]$ and $[SII]$ $\lambda\lambda 6717, 6731$ (Figure 29). Low S/N emission lines of $H\beta$ and $[OIII]$ $\lambda 5007$, as well as G band absorption, are also detected. The $EW(H\alpha+[NII]) = 52 \text{ \AA}$, which is near the upper limit for galaxies with normal star formation rates (K92). Line-intensity diagnostics lead to the classification of this galaxy as an HII galaxy (Figures 5 & 6).

The continuum increases toward the red over the observed wavelength range. The 41-50 color index is 0.48, which is redder than the sample average. The broadband colors for this galaxy are also moderately red. These data imply an average stellar population, consistent with the presence of G band absorption.

The prominent emission lines in the companion galaxy are $H\alpha+[NII]$ and $[OIII]$ $\lambda 5007$ (Figure 30). Low S/N lines of $H\beta$, $[OIII]$ $\lambda 4959$ and $[SII]$ $\lambda\lambda 6717, 6731$ are detected. The G band stellar absorption feature is also observed. The $EW(H\alpha+[NII]) = 50 \text{ \AA}$, which is near the upper limit for galaxies with normal star formation rates (K92). We classify this galaxy as an HII galaxy based on line-intensity diagnostics (Figures 5 & 6).

The continuum of the companion galaxy increases toward the blue between $4500 \text{ \AA}$ and $6500 \text{ \AA}$. At wavelengths longer than $6800 \text{ \AA}$, the spectrum increases gradually toward the red. This galaxy has a moderately blue 41-50 color index of

0.21, which is consistent with its broadband colors (C97). These continuum features indicate the presence of many hot O and B stars combined with a population of cool stars, in agreement with the presence of G band absorption.

1535+3831: No emission lines are detected from this galaxy (Figure 31). The mean flux from the continuum near the expected position of $H\alpha$ is 9.77×10^{-16} ergs/cm²/sec/Å. Employing the approximate detection limit discussed above, the $H\alpha$ + $[NII]$ flux must be less than 9.77×10^{-16} ergs/cm²/sec/Å. $H\beta$ might be present in absorption. The continuum of this galaxy increases sharply to the red between 4000 Å and 5000 Å, and more gradually to the red over the rest of the wavelength range. This continuum shape agrees well with the red broadband colors of this galaxy (C97).

1537+5315: This galaxy has a single elongated spiral arm or tidal tail (C97). No emission lines are detected from this galaxy (Figure 32). W95 also detected little or no $H\alpha$ emission from the galaxy. The mean flux from the continuum near the expected position of $H\alpha$ is 8.72×10^{-16} ergs/cm²/sec/Å. Employing the approximate detection limit discussed above, the $H\alpha$ + $[NII]$ flux must be less than 8.72×10^{-16} ergs/cm²/sec/Å. However, spectra of this galaxy were not taken under photometric conditions, and this flux limit is only an estimate, at best. The continuum of this galaxy increases sharply to the red between 4000 Å and 5000 Å, and more gradually to the red over the rest of the wavelength range. This continuum shape agrees well with the red broadband colors of this galaxy (C97).

The lack of emission from this galaxy is not necessarily inconsistent with its disturbed morphology. Kennicutt et al. (1987) have shown that tidal interactions do not always produce significant star formation episodes. Even when triggered, substantial star formation occurs on relatively short time scales. It is possible that the major star forming episode in this galaxy has already occurred.

1540+5013: The only emission line present in the spectrum of this galaxy is $H\alpha$ (Figure 33), with $EW(H\alpha) = 24 \text{ \AA}$, which is in the range for galaxies with normal star formations rates (K92). The G band stellar absorption feature is detected, and the $H\beta$ line might also be present in absorption. The continuum of this galaxy increases sharply to the red between $4000 \text{ \AA}$ and $4500 \text{ \AA}$, and more gradually to the red over the rest of the wavelength range. This continuum shape agrees well with the red broadband colors of this galaxy (C97).

1547+5121: This is an edge-on galaxy with an asymmetric disk. The only prominent emission feature from this galaxy is $H\alpha+[NII]$ (Figure 34). Low S/N $H\beta$, $[OIII]$ $\lambda\lambda 4959, 5007$ and $[SII]$ $\lambda\lambda 6717, 6731$ emission lines were detected, along with the Na D and Mg b stellar absorption bands. The $EW(H\alpha+[NII]) = 47 \text{ \AA}$, which is near the upper limit for galaxies with normal star formations rates (K92). Line-intensity diagnostics lead to the classification of this galaxy as an HII galaxy (Figures 5 & 6).

The continuum of this galaxy increases toward the blue between $4500 \text{ \AA}$ and $6500 \text{ \AA}$. At wavelengths longer than $6800 \text{ \AA}$, the spectrum increases gradually toward the red. This galaxy has a moderately blue 41-50 color index of 0.28, which

is consistent with its broadband colors (C97). These continuum features indicate the presence of hot O and B stars combined with a cooler stellar population, in agreement with the presence of Na D and Mg b absorption.

CHAPTER 7

MERGING GALAXY PAIRS

The galaxy systems 1510+4727 and 1517+3956 have asymmetric or disturbed morphologies (Moody et al. 1987, W95, C97). Both systems have a northern and southern bright nucleus, separated by approximately 4". Because of their unusual morphologies, we suspected that 1510+4727 and 1517+3956 might be merging or closely interacting galaxy pairs. Consequently, for each galaxy system, spectra were obtained to test for differences in redshift between the apparent nuclei. In both cases, shifts in the wavelengths of emission lines are observed (Figure 35 and Figure 36).

The slit on the grism spectrograph is oriented along an east-to-west line. This slit orientation is fixed and could not be rotated to observe both nuclei simultaneously. Thus, for each galaxy system, individual spectra of the northern and southern nuclei were taken. Because of the width of the slit, some contamination from one half of the system on the spectra of the other half is expected.

The average redshifts reported here for the components of each galaxy system were determined from the measured wavelengths of all the unblended

emission lines (6 in each case). Measured redshifts were then corrected for the sun's motion according to Eq. 1.

Differences in velocity (Δv) calculated from the average redshifts of the bright nuclei have relatively high calculated uncertainties, which arise from the uncertainties in the measured redshifts. These uncertainties most likely are due to errors in the absolute wavelength calibration of the spectra. However, because the same wavelength solution was used to calibrate each spectrum, the relative wavelength calibration between the spectra is quite consistent. This fact is verified by examining the features in the night-sky contribution from each spectrum (Figure 35 and Figure 36). The features in the night sky are well aligned over the entire wavelength region observed. Therefore, we calculated individual values of Δv for each of the unblended emission lines. From these values of Δv , we determined a mean Δv and a standard error. This process minimizes the effect of any wavelength-dependent errors in the calibration.

The redshift calculated for the northern bright nucleus in 1517+3956 is $z_{\text{corr}} = 0.0464 \pm 0.0007$. Only one exposure of this feature was taken. For the southern nucleus, $z_{\text{corr}} = 0.0479 \pm 0.0005$. Moody et al. (1987) published a recessional velocity for this system corresponding to $z = 0.0475$, which lies between the two redshifts given above. Line widths for both halves of the system were approximately 900-1100 km/sec, which is on the order of the resolution. The mean $\Delta v = 449 \pm 50$ km/s. This value is in agreement with the velocity difference between two carbon-monoxide (CO) emission features detected in radio observations of this galaxy (Sage et al. 1997). In the CO spectrum, $\Delta v = 497 \pm 24$ km/s.

Surprisingly, this velocity difference is not observed in the blended $H\alpha+[NII]$ and $[SII]$ lines (Figure 35). This fact is particularly puzzling considering that $H\alpha$ and $H\beta$ must be emitted from the same region of the galaxy. Systematic errors in the wavelength solution have been ruled out as a cause by examining the night-sky spectra. The positions of features in the night sky from each half of the galaxy are virtually identical (Figure 35). Therefore, the wavelength solution cannot be responsible for the observed shift in the unblended lines, or for the lack of a shift in $H\alpha+[NII]$ and $[SII]$.

A second anomaly is that the $H\alpha/H\beta$ decrement is less than 2.86 in the spectrum of the northern nuclei. This anomaly cannot be due to reddening, which would make the observed decrement greater than 2.86. Examination of the two-dimensional spectrum and the extraction parameters verified that all of the signal at $H\alpha$ had been included in the extraction aperture.

The cause of these discrepancies is unknown. One possibility is that different regions of the galaxy are being sampled at different wavelengths. This type of error can arise due to atmospheric differential refraction. However, observations of 1517+3956 were made at the relatively low airmass of approximately 1.09. At this airmass, the spatial discrepancy between points 4500 Å and 7000 Å is estimated to be only 0.36" (Filippenko 1982), making this scenario unlikely. It is conceivable that the inconsistencies are due to some type of instrumental problem within the spectrograph which produced spurious results for the red end of the spectrum of the northern nucleus. Ultimately, additional spectra of this object will be needed to completely resolve this question.

Because of the presence of these anomalies, we sought additional verification of the velocity difference in our spectra of 1517+3956. Fourier cross-correlation analysis, similar to the method described by Tonry and Davis (1979), was implemented to determine the shift in wavelength between the spectra from the two bright regions in this galaxy system. This method does not rely solely on positions of the bright emission lines. Instead, it correlates all of the features of the spectrum, including any stellar absorption features and structure in the continuum.

This analysis reveals a velocity difference between the two bright nuclei of 400 ± 66 km/sec. The uncertainty is estimated by dividing the FWHM of the cross-correlation peak by the signal to noise ratio in the cross-correlation function. This value is in good agreement with Δv from the unblended emission lines. Therefore, we conclude that the velocity difference in 1517+3956 is real with $\Delta v = 449 \pm 50$ km/s.

For 1510+4727, the case is much more straightforward (Figure 36). From the southern nucleus of 1510+4727, we measure a redshift of $z_{\text{corr}} = 0.0543 \pm 0.0004$. The redshift for the northern nucleus is $z_{\text{corr}} = 0.0529 \pm 0.0006$. Moody et al. (1987) published a recessional velocity for this system corresponding to $z = 0.0535$, which lies between the two redshifts given above. Line widths for both halves of the system are approximately 900-1000 km/sec, which is on the order of the resolution. The mean $\Delta v = 420 \pm 25$ km/s. A velocity difference of approximately the same magnitude is also observed in the blended $H\alpha$ + $[NII]$ and $[SII]$ lines (Figure 36).

A Fourier cross-correlation analysis of the combined spectra from each half of 1510+4727 yields a velocity difference between the two bright regions of $388 \pm$

21 km/sec. Within the combined uncertainties, this value of Δv is consistent with that derived from the emission lines. Therefore, we conclude that the two nuclei of 1510+4727 have a difference in velocities of $\Delta v = 420 \pm 25$ km/s.

Because of the unusual morphologies, prominent emission features and observed internal velocity differences of these systems, we conclude that 1510+4727 and 1517+3956 are merging or closely interacting galaxy pairs. This result was previously suggested for 1517+3956 by Weistrop (1994) and for 1510+4727 by C97. The implications of these results are discussed in Chapter 9.

CHAPTER 8

RESULTS

Emission lines and absorption features were identified in 23 of the 26 void galaxies examined. This number includes 1517+3949, in which optical emission lines were identified for the first time. No emission or absorption features were detected in the spectra of 1503+5428, 1535+3831 and 1537+5315. Upper limits for line emission from these galaxies based on continuum flux are discussed in Chapter 6.

For the remaining 23 galaxies, redshifts were calculated using all of the available lines. To test the accuracy of our wavelength calibration and method of line measurement, the measured redshifts were compared to redshifts of the galaxies published by other authors. Nearly all of the measured redshifts agree with the published redshifts within the uncertainty of the measurement.

For galaxies in the sample with measurable $H\alpha+[NII]$ emission, the $EW(H\alpha+[NII])$ are compared to samples of field and cluster galaxies having $H\alpha$ emission (KK83 and K92). In the comparison samples, a correlation was identified between the $EW(H\alpha+[NII])$ and the star formation rate. Galaxies with normal rates

of star formation are found to have $EW(H\alpha+[NII]) \leq 40 \text{ \AA}$ (K92). Galaxies with $EW(H\alpha+[NII]) \geq 50 \text{ \AA}$ are experiencing powerful starburst episodes (KK83).

Of the 23 void galaxies with measurable $H\alpha+[NII]$ lines, 11 have $EW(H\alpha+[NII]) \geq 50 \text{ \AA}$. Six of these galaxies have $EW(H\alpha+[NII]) \geq 88 \text{ \AA}$, the mean value for a sample of ultra-luminous IRAS mergers (Liu et al. 1995). These large values for $EW(H\alpha+[NII])$ indicate violent star formation activity among many of the void galaxies.

Sixteen of the void galaxies have sufficient emission lines to examine line-intensity diagnostics and classify them as HII galaxies or AGNs. Using these diagnostics, fourteen galaxies in the sample are found to be HII galaxies. Two of these systems 1432+5302 and 1507+4554 are classified as ESBs (extreme starburst galaxies, Allen et al. 1991). ESBs are described as the youngest examples of major star formation episodes. Five of the galaxies in our sample have emission lines in their spectra, but do not have the lines necessary for classification. These galaxies have also not been classified by other authors. Therefore, the classification for these galaxies remains unknown. This group includes 1345+4641, 1407+4840, 1413+5056, 1517+3949, and 1540+5013.

The analysis of line-intensity diagnostics has also led to the identification of the galaxy 1458+4944 as an AGN, for the first time. This galaxy is classified as a LINER because it has $\lambda 5007/H\beta < 3$. Another galaxy, 1406+4905, was previously classified as a LINER by PTP. Our analysis of this galaxy is consistent with this result, although somewhat uncertain. Including these two galaxies, at least five AGNs are known within the Bootes Void. The other three are 1428+5255 (Seyfert

2), 1506+5138 (Seyfert 1) and 1519+5050 (CG 693, Seyfert 1). Because of the large slit through which these spectra were obtained, stellar emission from the surrounding galaxy could overpower nuclear emission lines. Therefore, the number of AGNs in the void might be underestimated. A summary of the classifications of the void galaxies is given in Table 6.

For purposes of comparison, the relative line-intensities of a sample of ELGs from K92 (his Table 1) and a sample of galaxy mergers from Liu et al. (1995, their Table 2) are plotted with the void galaxies in Figures 37 & 38. In Figure 38, the void galaxies appear to follow the distribution of ELGs closely. In Figure 37, however, the void galaxies seem to be much more tightly clustered around the transition zone. This distribution might indicate slightly greater flux in [SII] $\lambda\lambda 6717, 6731$ among the void sample than in the field galaxies. This enhancement in [SII] emission was also observed by PTP.

Cohen (1976) has shown a strong correlation between the strength of Balmer emission and galaxy color. KK83 and K92 have verified the correlation between emission line EW and broadband colors, or continuum colors, respectively. For each galaxy in this sample, the shape of the continuum is examined and the 41-50 spectral color index is measured to help characterize the stellar population. The 41-50 color index is plotted against the $EW(H\alpha + [NII])$ in Figure 39 for the void galaxy sample, the emission line sample of K92, and the mergers of Liu et al. (1995). In this figure, the void galaxies fall neatly onto the sequence defined by the majority of the ELGs. Thus, the standard correlation between Balmer emission and continuum color is also seen in the void galaxies.

Table 6. Classifications for the Bootes Void Galaxies

Galaxy (1)	Type (2)	Comments (3)
1345+4641	Unknown	
1357+4641	HII	
1406+4905	AGN	LINER
1407+4840	Unknown	
1408+4852	HII	
1413+5056	Unknown	
1428+5255	AGN	Seyfert 2
1432+5302	ESB	
1444+4402	HII	
1446+4457	HII	
1457+4228	HII	
1458+4944	AGN	LINER
1503+5428	Unknown	No lines observed
1505+3958	HII	
1506+5138	AGN	Seyfert 1
1507+4554	ESB	
1510+4727	HII	
1517+3949	Unknown	
1517+3956	HII	
1519+5050	HII	(CG 692)
1519+5050	AGN	(CG 693) Seyfert 1
1530+4332	HII	(Main)
1530+4332	HII	(Companion)
1535+3831	Unknown	No lines observed
1537+5315	Unknown	No lines observed
1540+5013	Unknown	
1547+5121	HII	

Nine galaxies in our sample have continuum shapes that increase strongly toward the blue at wavelengths shorter than 5500 Å (see Chapter 6). Nearly all of these galaxies have strong emission lines, and only three of them have stellar absorption features detected in their spectra. These data imply a significant fraction of O and B stars present within these galaxies, which dominate the continuum.

Fifteen of the galaxies in our sample have continuum shapes that increase toward the red, either at wavelengths greater than 6500 Å or over the entire wavelength range. This rise in the red continuum suggests either an underlying population of late-type dwarf stars or a significant fraction of young, red supergiant stars, depending on the fraction of O and B stars. The galaxies with continua which increase to the red at all wavelengths also tend to have prominent absorption features in their spectra. These data confirm the presence of older stellar populations within this group of galaxies.

Of the galaxies in this sample with stellar absorption features, 2/3 are IRAS galaxies. This relationship implies a correlation between the presence of older stars and significant amounts of warm dust within these void galaxies. Thus, evidence for some metal enrichment is observed in these galaxies. Other than this relationship, no major trends are found among the void galaxies that were detected by IRAS and those that were not. For instance, the numbers of galaxies with strong star formation activity or nuclear activity are distributed evenly between these two groups. Therefore, no strong correlations are established between the properties of the void galaxies and the presence of infrared emission.

The continuum shapes and 41-50 colors of the void galaxies are well correlated with the broadband colors measured by C97. This correlation serves to substantiate the accuracy of both data sets, and strengthens the conclusions drawn from them.

From examination of the imaging data on these galaxies (C97), it was suspected that two irregular galaxy systems, 1510+4727 and 1517+3956, might be merging galaxy pairs with double nuclei. Analysis of spectra taken across each half of the individual systems reveals significant, systematic velocity differences among the emission lines. For 1510+4727, the nuclei have a velocity difference of $\Delta v \approx 420 \pm 25$ km/s. For 1517+3956, the velocity difference between the nuclei is $\Delta v \approx 449 \pm 50$ km/s. In the latter case, some disagreement exists between the blended and unblended emission lines (Chapter 7). However, the velocity difference is in agreement with the CO data of Sage et al. (1997). This system has also been identified as a megamaser, suggesting violent star formation activity (Bottinelli et al. 1989).

With the addition of 1510+4727 and 1517+3956, at least four galaxy pairs are known within the Bootes Void. The other two pairs are 1519+5050 and 1530+4332. Three of the galaxy pairs are either merging or strongly interacting.

Using line-intensity diagnostics, PTP have classified the merging pair, 1510+4727, as an HII galaxy. Indeed, in our data, 1510+4727 lies among the HII galaxies with the highest states of ionization in Figure 5. However, in the other two diagnostic diagrams (Figures 6 & 7), this system is located within the transition

zone on the side of the AGNs. It is possible that one of the nuclei in this system is harboring an AGN.

CHAPTER 9

CONCLUSIONS AND DISCUSSION

This study has characterized the properties of a sample of galaxies in the Bootes Void. The spectra of 26 galaxies from the sample of 27 Bootes Void galaxies defined by C97 were analyzed. Emission lines and absorption features were detected in 23 of these galaxies, including (for the first time) 1517+3949. The majority are HII galaxies with properties similar to HII galaxies in the field. Approximately 48% of these HII galaxies have elevated rates of star formation, based on the equivalent widths of $H\alpha+[NII]$. Seven of the HII galaxies have morphology suggesting star formation triggered by tidal interactions (C97).

Analysis of the continuum shapes and 41-50 color indices indicate good agreement with the photometric results of C97. Examination of the galaxy continua suggest that approximately 1/3 of the void galaxies have large populations of blue stars. Stellar absorption features are observed in over half the galaxies in the sample, implying the presence of an older stellar population. A correlation between the presence of stellar absorption and detection by IRAS implies that a portion of the void sample has metallicity similar to field galaxies.

The galaxy 1458+4944 is found to be a LINER from ratios of its emission lines. The galaxy system 1510+4727 also has line ratios that suggest it might contain an AGN. However, this result is more ambiguous. Including only 1458+4944, the number of known AGNs in the Bootes Void is now five. This number indicates that ~20% of the ELGs in the void are AGNs, which is large compared to ~11% of field ELGs which are AGNs (Salzer et al. 1989). Again, the small numbers involved make the significance of this result uncertain.

The presence of two ESB galaxies indicates that some violent star formation is taking place in the current epoch. However, evidence of older, metal-rich stellar populations in many of the galaxies demonstrates that the void galaxies are not experiencing their first generation of star formation.

Two merging or closely interacting galaxy pairs are identified for the first time. Spectra of the irregular galaxies 1510+4727 and 1517+3956 indicate velocity differences between their components of 420 ± 25 km/s and 449 ± 50 km/s, respectively. With the addition of these two galaxies, the total number of galaxy pairs in the void is four, with three pairs strongly interacting. This number suggests a greater occurrence of galaxy pairs in the void than the 8% reported for field emission line galaxies by Salzer et al. (1989), although this conclusion is uncertain due to the small numbers involved. However, this result does agree with the conclusion of W92 that conditions for producing galaxy interactions are independent of galaxy density, provided that all regions within the void are uniformly under-dense.

The primary goal behind the study of galaxies in low-density environments is to define the void population and to determine how the characteristics of void galaxies fit in with the larger questions concerning galaxy formation and evolution, and the large-scale distribution of mass in the universe.

Because of the selection effects involved in defining the sample of Bootes Void galaxies, the properties determined for this sample cannot be generalized to define a representative void population. However, these galaxies are certainly an important segment of the galaxy population in the Bootes Void. Therefore, the existence of active, star-forming and tidally interacting galaxies in voids provides constraints for any models of galaxy evolution in low-density environments.

The models of Hoffman et al. (1992) suggest that voids should be inhabited by giant low surface brightness galaxies. Lacey et al. (1993) state that their models predict no luminous galaxies forming in voids due to a lack of tidal interactions needed to trigger star formation. These conclusions are inconsistent with the results from this sample of Bootes Void galaxies, which depict ELGs very similar to those in the field.

By examining the distribution of the IRAS galaxies in the Bootes Void, Weistrop (1994) identified a vertical slab 10 Mpc wide which contained approximately half of these galaxies. This structure is also present in the distribution of our entire sample, and the galaxy density within it is comparable to the density outside the void (Weistrop 1994). This result is consistent with S96, who find that many of the Bootes Void galaxies have small HI companions nearby, suggesting spatial correlations among void galaxies. Popescu et al. (1997) identified ELGs in

nearby voids. Although dealing with small numbers of galaxies, they report a tendency for clustering among void galaxies and even identify a filamentary structure in one void which they termed "the Arch." Models by van de Weygaert & van Kampen (1993) and Dubinski et al. (1993) predict nonuniform filamentary distributions of matter to evolve within voids.

The conclusions reached in these studies are consistent with the implications from our data on the Bootes Void galaxies. It is possible that the evolution of galaxies in voids is strongly tied to mass filaments within the voids. The bright, active or star-forming galaxies found in voids could have evolved along filaments which provide environments where the local mass density is similar to that in the field.

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Figure 1 Examples of the templates used to deblend the H α + [NII] complex. The solid line in (a) is the blended template for the galaxy 1457+4228. This template is the sum of the individual H α and [NII] templates, shown by the two dashed lines in (a). The H α and [NII] templates are plotted alone in (b) and (c), respectively. The fractional intensities (y-axes) of the templates in Figure 1 are relative to the peak intensity of the H α + [NII] complex of 1457+4228.

Deblending $H\alpha$ and $[NII]$

Figure 2 Examples of deblending the $H\alpha+[NII]$ complex for four galaxies in the sample. All of the spectra in Figure 2 have been normalized to the peak intensity of the $H\alpha+[NII]$ complex of the respective galaxies. The solid line in each figure is the $H\alpha+[NII]$ complex from the galaxy spectrum, with the local continuum subtracted. The upper dashed under the $H\alpha+[NII]$ complex is the blended template. The lower dashed line is the residual spectrum. The fit to the relatively high S/N $H\alpha+[NII]$ complex from the galaxy 1457+4228 is shown in (a). The fit to the low S/N complex of 1517+3949 is shown in (b). 1505+3958 has relatively strong $[NII]$ emission, while 1507+4554 has only a weak $[NII]$ contribution [(c) and (d), respectively].

Continuum Shapes

Figure 3 Examples of fitting the continuum shapes of four galaxies. The spectra shown have been normalized to the flux at 5500 Å. The dashed line is the fit to each continuum. The continuum shown in (a) increases toward the red, (b) increases toward the blue, (c) shows only small variations over most of the wavelength range, and (d) has an unusual continuum shape. The continuum shapes of these galaxies are discussed in detail in Chapter 6.

Figure 4 The S/N in the [OIII] $\lambda 4959$ line is plotted against the difference between the measured $\lambda 4959/\lambda 5007$ intensity ratio and the theoretical $\lambda 4959/\lambda 5007$ ratio of 0.33. The dashed line represents $\lambda 4959$ S/N = 25. The spread in the difference between the measured and theoretical values of the $\lambda 4959/\lambda 5007$ line ratio is much greater for $\lambda 4959 < 25$ (see Section 5.6).

Figure 5 Reddening corrected $[\text{OIII}] \lambda 5007/\text{H}\beta$ vs. $[\text{SII}] (\lambda 6717 + \lambda 6731)/\text{H}\alpha$ intensity ratios. The filled circles are the void galaxies from the sample in this paper for which the necessary emission lines were detected. 2σ error bars are shown and represent the propagated uncertainty in the line ratios. The triangles are the ten void galaxies observed by PTP. 2σ error bars are also shown for the PTP data. The galaxies are identified by letters; upper case for this sample and lower case for the sample of PTP. The key for the identifications is given in the caption of Figure 6, and is the same for Figures 5-7. The solid curve is the division between AGNs and HII galaxies defined by VO87, with the AGNs on the right (see Section 5.7). The scales of Figures 5-7 were chosen to match those of VO87. The inset in this figure is a magnification of the boxed region where the galaxies are tightly clustered.

Figure 6 Reddening corrected $[OIII] \lambda 5007/H\beta$ vs. $[NII] (\lambda 6583)/H\alpha$ intensity ratios. Symbols are the same as in Figure 5. The key to the galaxy identifications for Figures 5-7 is given below. The galaxies are identified by letters; upper case for this sample and lower case for the sample of PTP. Not all galaxies appear in every figure.

1357+4641 (A)	1446+4457 (F,f)	1510+4727 (K,k)	1530+4332:
1406+4905 (B,b)	1457+4228 (G,g)	1517+3956 (L,l)	(Companion - P)
1408+4852 (C,c)	1458+4944 (H)	1519+5050 (M)	1547+5121 (Q)
1432+5302 (D,d)	1505+3958 (I,i)	1530+4332:	1506+5138 (r)
1444+4402 (E)	1507+4554 (J,j)	(Main - N)

Figure 7 Reddening corrected [OIII] λ 5007/H β vs. [OI] (λ 6300)/H α intensity ratios. Symbols are the same as in Figure 5. The key for the identifications is given in the caption of Figure 6.

Figure 8 Published redshifts vs. measured redshifts for the 21 galaxies observed which had measurable emission lines. The line represents a linear least-squares fit to the data. The slope of the fit is 0.964 and the y-intercept is 0.0015, indicating good agreement between the published and measured redshifts.

Figure 9 Spectrum of 1345+4641, normalized to the flux at 5500 Å (1.00×10^{-16} ergs $\text{cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$). The spectrum of this galaxy was provided by SSG. The spectral features indicated are discussed in Chapter 6.

Figure 10 Spectrum of 1357+4641, normalized to the flux at 5500 Å (1.00×10^{-16} ergs $\text{cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$). The spectrum of this galaxy was provided by SSG. The spectral features indicated are discussed in Chapter 6.

Figure 11 Spectrum of 1406+4905 (I Zw 81), normalized to the flux at 5500 Å ($3.16 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was not observed on a photometric night. The spectral features indicated are discussed in Chapter 6.

Figure 12 Spectrum of 1407+4840 (CG 910), normalized to the flux at 5500 Å ($9.70 \times 10^{-16} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was observed on a photometric night. The spectral features indicated are discussed in Chapter 6. The feature marked N.S. is the result of incomplete night-sky subtraction.

Figure 13 Spectrum of 1408+4852 (CG 370), normalized to the flux at 5500 Å ($5.90 \times 10^{-16} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was observed on a photometric night. The spectral features indicated are discussed in Chapter 6. The feature marked N.S. is the result of incomplete night-sky subtraction.

Figure 14 Spectrum of 1413+5056, normalized to the flux at 5500 Å (6.70×10^{-16} ergs $\text{cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$). This galaxy was not observed on a photometric night. The spectral features indicated are discussed in Chapter 6. The feature marked N.S. is the result of incomplete night-sky subtraction.

Figure 15 Spectrum of 1428+5255, normalized to the flux at 5500 Å (2.50×10^{-15} ergs $\text{cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$). This galaxy was observed on a photometric night. The spectral features indicated are discussed in Chapter 6.

Figure 16 Spectrum of 1432+5302 (CG 474), normalized to the flux at 5500 Å ($1.02 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was observed on a photometric night. The spectral features indicated are discussed in Chapter 6. The feature marked N.S. is the result of incomplete night-sky subtraction.

Figure 17 Spectrum of 1444+4402 (CG 538), normalized to the flux at 5500 Å ($1.60 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was observed on a photometric night. The spectral features indicated are discussed in Chapter 6. The feature marked N.S. is the result of incomplete night-sky subtraction.

Figure 18 Spectrum of 1446+4447 (CG 547), normalized to the flux at 5500 Å ($2.35 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was observed on a photometric night. The spectral features indicated are discussed in Chapter 6. The feature marked N.S. is the result of incomplete night-sky subtraction.

Figure 19 Spectrum of 1457+4228 (CG 598), normalized to the flux at 5500 Å ($2.31 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was observed on a photometric night. The spectral features indicated are discussed in Chapter 6. The feature marked N.S. is the result of incomplete night-sky subtraction.

Figure 20 Spectrum of 1458+4944 (CG 922), normalized to the flux at 5500 Å ($9.50 \times 10^{-16} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was observed on a photometric night. The spectral features indicated are discussed in Chapter 6. The feature marked N.S. is the result of incomplete night-sky subtraction.

Figure 21 Spectrum of 1503+5428 (CG 620), normalized to the flux at 5500 Å ($1.32 \times 10^{-16} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was not observed on a photometric night. The spectrum of this galaxy is discussed in Chapter 6. The feature marked N.S. is the result of incomplete night-sky subtraction.

Figure 22 Spectrum of 1505+3958 (CG 629), normalized to the flux at 5500 Å ($1.23 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was observed on a photometric night. The spectral features indicated are discussed in Chapter 6. The feature marked N.S. is the result of incomplete night-sky subtraction.

Figure 23 Spectrum of 1506+5138 (Mrk 845), normalized to the flux at 5500 Å ($1.03 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was observed on a photometric night. The spectral features indicated are discussed in Chapter 6. The feature marked N.S. is the result of incomplete night-sky subtraction.

Figure 24 Spectrum of 1507+4554 (CG 642), normalized to the flux at 5500 Å ($1.52 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was not observed on a photometric night. The spectral features indicated are discussed in Chapter 6. The feature marked N.S. is the result of incomplete night-sky subtraction.

Figure 25 Spectrum of 1510+4727 (CG 657), normalized to the flux at 5500 Å ($4.00 \times 10^{-16} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was observed on a photometric night. The spectral features indicated are discussed in Chapter 6.

Figure 26 Spectrum of 1517+3949, normalized to the flux at 5500 Å (2.90×10^{-16} ergs $\text{cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$). This galaxy was not observed on a photometric night. The spectral features indicated are discussed in Chapter 6.

Figure 27 Spectrum of 1517+3956 (CG 684), normalized to the flux at 5500 Å ($9.20 \times 10^{-16} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was observed on a photometric night. The spectral features indicated are discussed in Chapter 6. The feature marked N.S. is the result of incomplete night-sky subtraction.

Figure 28 Spectrum of 1519+5050 (CG 692), normalized to the flux at 5500 Å ($1.09 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was not observed on a photometric night. The spectral features indicated are discussed in Chapter 6.

Figure 29 Spectrum of 1530+4332 (main galaxy), normalized to the flux at 5500 Å ($7.70 \times 10^{-16} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was observed on a photometric night. The spectral features indicated are discussed in Chapter 6.

Figure 30 Spectrum of 1530+4332 (companion galaxy), normalized to the flux at 5500 Å ($4.50 \times 10^{-16} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$). This galaxy was observed on a photometric night. The spectral features indicated are discussed in Chapter 6. The flat features in the spectrum between 6000 Å and 6500 Å are the result of bad pixels on the CCD.

Figure 31 Spectrum of 1535+3831, normalized to the flux at 5500 Å (9.15×10^{-16} ergs $\text{cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$). This galaxy was observed on a photometric night. The spectrum of this galaxy is discussed in Chapter 6. The feature marked N.S. is the result of incomplete night-sky subtraction.

Figure 32 Spectrum of 1537+5315, normalized to the flux at 5500 Å (8.72×10^{-16} ergs $\text{cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$). This galaxy was not observed on a photometric night. The spectrum of this galaxy is discussed in Chapter 6. The feature marked N.S. is the result of incomplete night-sky subtraction.

Figure 33 Spectrum of 1540+5013 normalized to the flux at 5500 Å (1.30×10^{-15} ergs $\text{cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$). This galaxy was not observed on a photometric night. The spectral features indicated are discussed in Chapter 6.

Figure 34 Spectrum of 1547+5121, normalized to the flux at 5500 Å (5.40×10^{-16} ergs $\text{cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$). This galaxy was not observed on a photometric night. The spectral features indicated are discussed in Chapter 6.

1517+3956 - Galaxy Pair

Figure 35 Spectra of the two nuclei of 1517+3956 (CG 684), normalized to the flux at 5500 $\text{\AA}$. The solid line in (a) and (b) is the southern nucleus and the dashed line is the northern nucleus. (a) is an expanded plot of the blue end of the spectrum and (b) is an expanded plot of the red end. (c) and (d) show each end of the spectrum with the contribution from the night sky to the spectrum of each nucleus overplotted (see Chapter 7).

1510+4727 - Galaxy Pair

Figure 36 Spectra of the two nuclei of 1510+4727 (CG 657), normalized to the flux at 5500 Å. The solid line in (a) and (b) is the southern nucleus and the dashed line is the northern nucleus. (a) is an expanded plot of the blue end of the spectrum and (b) is an expanded plot of the red end. (c) and (d) show each end of the spectrum with the contribution from the night sky to the spectrum of each nucleus overplotted (see Chapter 7).

Figure 37 Reddening corrected [OIII] λ 5007/H β vs. [SII] (λ 6717+ λ 6731)/H α intensity ratios. The filled circles are the void galaxies from the sample in this paper for which the necessary emission lines were detected. 2σ error bars are shown and represent the propagated uncertainty in the line ratios. The unfilled circles are the sample of ELGs from K92. The triangles are the sample of galaxy mergers from Liu et al. (1995). The solid curve is the division between AGNs and HII galaxies defined by VO87.

Figure 38 Reddening corrected [OIII] λ 5007/H β vs. [NII] (λ 6583)/H α intensity ratios. Symbols are the same as in Figure 37.

Figure 39 Equivalent width of the H α + [NII] complex vs. the 41-50 continuum color index for the 21 galaxies observed which had measurable H α + [NII] emission. 1σ error bars are shown and represent the propagated uncertainty in the Log EW(H α + [NII]) in the y-direction and the 41-50 color in the x-direction. The unfilled circles are the sample of ELGs from K92. The triangles are the sample of galaxy mergers from Liu et al. (1995).

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Dr. Robert W. Milkey
Executive Officer

July 10, 1997

Shawn Cruzen
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Dear Shawn,

This letter will confirm permission for you to use portions of the material listed below, published by you in the Astronomical Journal. This material will be used in preparation of your dissertation.

"Photometry of Galaxies in the Bootes Void", June 1997, vol. 113 (6), p. 1983.

Sincerely yours,

Jane Crane
Assistant to the Executive Officer