THE COOL STELLAR POPULATIONS OF EARLY-TYPE GALAXIES AND THE GALACTIC BULGE

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

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1995

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To Mom and Tim

ACKNOWLEDGEMENTS

First and foremost, I would like to express my deepest appreciation to my mother, Darlene, and my brother, Tim, for their unwavering support before, during, and (hopefully) after my graduate studies. Without them, I would not have achieved as much as I have nor be as happy as I am. Thank you, Mom and Tim, for all that you have done for me.

Obviously, I am deeply indebted to my advisor, Jay Frogel, for his support (both financial and otherwise), his scientific expertise and his belief in my abilities. He suggested the initial dissertation project to me and helped me to redefine it along the way, always remaining positive and encouraging. I would also like to thank the other members of my dissertation committee, Don Terndrup and Kris Sellgren, for their endless patience and understanding and for their thorough review of my research and written dissertation. A special thanks go to Bob Wing, who read this dissertation and became a substitute member of my defense committee on very short notice. Rick Pogge is acknowledged for many helpful scientific discussions, and Brad Peterson and Jerry Newsom were always positive and concerned for my welfare. I would like to thank Pat Osmer as well; he was instrumental in making the special arrangements necessary for me to be able to complete this work.

I would like to express my gratitude to the Ohio State University and Lowell Observatory for granting me the observing time required to undertake this dissertation research. I owe Mark Wagner and Ray Bertram a great debt for their assistance at Lowell Observatory. In addition, Bob Millis went out of his way to make my visits there as productive and comfortable as possible. I would also like to thank the staff at Kitt Peak National Observatory for their outstanding service during my observing time there - Richard Elston is especially noted for his time and advice regarding the use of the CRSP instrument.

I can't express enough gratitude to the many friends I have made while at The Ohio State University. Many of the "old-timers" from the astronomy department have moved on to bigger and better things: Andy Karam, Mike Fisher, Pedro Saizar, Bill Welsh, Tereasa Brainerd, Cathy Mansperger, Kirk Korista, and Phil Martell. Current OSU graduate students Bob Blum, Glenn Tiede, Leslie Kuchinski, Mike Owen, Anita Krishnamurthi, Nancy Jo Lame, Ani Thakar, Babar Ali and Cheongho Han are thanked for their valuable scientific discussion but are most appreciated for their friendship and encouragement. I will miss them and wish them all the best. Other close friends who were critical to my success include Steve Long, Jens Villumsen, Mark Duell, Fernando Fischer and Rosa Gimenez. Karen Keppler is owed a very special thanks - she was always there to help and was a constant source of optimism, support and chocolate.

To the members of CURB (Clean-Up and Recycling Backers), my gratitude for giving me the opportunity to do something worthwhile besides astronomy and to give

something back to the community in which I lived. Shirley Cotter, Reardon Young, Mark Carter, Tom Brown *et al.* are a very special group of caring people. Among my many CURB-mates, I would especially like to thank Anthony Fabro for his friendship and for the rides he provided to CURB meetings and other recycling activities.

Finally, I am indebted to Brennan's Coffee Shop (and Yogurt Oasis) for supplying the caffeine necessary for survival on those late nights at the office and for providing various other forms of inspiration and motivation! Damon's Restaurant and NTN trivia also provided much-needed diversions from the daily grind.

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"A Comparison of the Near-Infrared Spectral Features of Early-Type Galaxies in the Coma Cluster, the Virgo Cluster and the Field," Houdashelt, M. L., and Frogel, J. A., in *The Evolution of Galaxies and Their Environment*, Proceedings of the Third Teton

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"A Comparison of the Near-Infrared Spectral Features of Early-Type Galaxies in the Virgo and Coma Clusters," Houdashelt, M. L., Columbus AAS meeting, June 1992. BAAS, 24, 808.

"The Red Supergiants of NGC 2100," Wing, R. F., and Houdashelt, M. L., Columbus AAS meeting, June 1992. BAAS, 24, 773.

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TABLE OF CONTENTS

DEDICATION	ii
ACKNOWLEDGEMENTS	iii
VITA	vi
LIST OF TABLES	xi
LIST OF FIGURES	xiv
CHAPTER	PAGE
I INTRODUCTION	1
1.1 Photometry of Early-Type Galaxies	4
1.1.1 The Color-Magnitude Relation	4
1.1.2 Color Gradients in Early-Type Galaxies	7
1.1.3 Colors and Stellar Populations	8
1.2 Spectroscopy of Early-Type Galaxies	8
1.3 This Dissertation	9
II OBSERVATIONS AND DATA REDUCTION	12
2.1 The Galaxy Sample	12
2.1.1 Data Taken from the Literature	13
2.2 Red Spectroscopy	15
2.2.1 Observations	16
2.2.2 Data Reduction	18
2.2.3 Near-Infrared Spectroscopy	24

III	RED SPECTRAL FEATURES IN EARLY-TYPE GALAXIES	33
3.1	Red Spectral Features in Stars	33
3.1.1	Atomic Lines	34
3.1.2	Molecular Bands	38
3.2	Measurement of Spectral Features in Galaxies	39
3.2.1	Definitions of the Indices	40
3.2.2	Measurement of the Indices	41
3.2.3	K-Corrections to CO Photometry	43
3.3	Trends in Early-Type Galaxy Nuclei	45
3.3.1	The Virgo Galaxies	45
3.4	Comparison of the Virgo, Coma and Field Galaxies	49
IV	MODELS OF THE GALACTIC BULGE	75
4.1	General Description of the Models	76
4.2	The Galactic Bulge M Giant Surveys	81
4.2.1	Photometry	82
4.2.2	Spectroscopy	83
4.2.3	Comments on the Bulge M Giant Data	87
4.3	The Baade's Window Model	90
4.3.1	The Color-Magnitude Diagram	91
4.3.2	The <i>I</i> -band Luminosity Function	96
4.3.3	The Model Calibration Relations	97
4.3.4	The Basic Baade's Window Model	104
4.3.5	Uncertainties in the Basic Baade's Window Model	105
4.3.6	Models of the Bulge as a Function of Radius	110
V	DISCUSSION	184
5.1	The Baade's Window Model	184
5.1.1	Comparison to Previous Baade's Window Models	185
5.1.2	The Distance to the Galactic Bulge	190
5.1.3	The Baade's Window Color-Magnitude Diagram	192
5.1.4	The Baade's Window Luminosity Function	196
5.1.5	The Metallicity of the Baade's Window Stars	197
5.1.6	Comparison to E/S0 Galaxy Nuclei	204
5.2	Radial Gradients in the Galactic Bulge	205

5.2.1	Simulating the Inner Galactic Bulge	207
5.2.2	Comparison to E/S0 Galaxy Nuclei	210
VI	CONCLUSIONS	231
	BIBLIOGRAPHY	235

LIST OF TABLES

TABLE	PAGE
1 The Early-Type Galaxy Sample	29
2 The Spectral Indices	51
3 The Atomic Line Index Measurements	52
4 The Molecular Band Index Measurements	53
5 The CO Index Measurements	54
6 Linear Least-Squares Fits to the Virgo Spectral Indices	55
7 The Extinction and Reddening of the Galactic Bulge Fields	116
8 The Molecular Band Indices of the M2+ Giants in the Sgr I Field . .	117
9 The Atomic Line Indices of the M2+ Giants in the Sgr I Field . . .	118
10 The Molecular Band Indices of the K-M1 Giants in the Sgr I Field . .	119
11 The Atomic Line Indices of the K-M1 Giants in the Sgr I Field . . .	120
12 The Molecular Band Indices of the M2+ Giants in Baade's Window .	121
13 The Atomic Line Indices of the M2+ Giants in Baade's Window . . .	122
14 The Molecular Band Indices of the K-M1 Giants in Baade's Window	123

15	The Atomic Line Indices of the K-M1 Giants in Baade's Window . .	124
16	The Molecular Band Indices of the M2+ Giants in the -6° Field . . .	125
17	The Atomic Line Indices of the M2+ Giants in the -6° Field	126
18	The Molecular Band Indices of the K-M1 Giants in the -6° Field . . .	127
19	The Atomic Line Indices of the K-M1 Giants in the -6° Field	128
20	The Molecular Band Indices of the M2+ Giants in the -8° Field . . .	129
21	The Atomic Line Indices of the M2+ Giants in the -8° Field	130
22	The Molecular Band Indices of the K-M1 Giants in the -8° Field . . .	131
23	The Atomic Line Indices of the K-M1 Giants in the -8° Field	132
24	The Molecular Band Indices of the M2+ Field Giants	133
25	The Atomic Line Indices of the M2+ Field Giants	134
26	The Molecular Band Indices of the K-M1 Field Giants	135
27	The Atomic Line Indices of the K-M1 Field Giants	136
28	The Molecular Band Indices of the Field Dwarfs	137
29	The Atomic Line Indices of the Field Dwarfs	138
30	The Definitions of the Baade's Window Models	139
31	The Integrated Photometry of the Baade's Window Models	140
32	The Integrated Molecular Band Indices of the Baade's Window Models	141
33	The Integrated Atomic Line Indices of the Baade's Window Models .	142

34	The Average Offsets from the Baade's Window Calibration Relations	143
35	The Integrated Photometry of the Galactic Bulge Models	144
36	The Integrated Molecular Band Indices of the Galactic Bulge Models	145
37	The Integrated Atomic Line Indices of the Galactic Bulge Models . .	146
38	A Comparison of Baade's Window Models	219
39	A Comparison of the Virgo E/S0 Galaxy Trends and the Galactic Bulge Model Gradients	220

LIST OF FIGURES

FIGURE		PAGE
1	The Galaxy Sample	30
2	Estimating the Central Velocity Dispersions of NGC 4124 and NGC 2723	31
3	Telluric Absorption Features in the Red Spectra	32
4	The Red Spectral Indices	56
5	Estimation of the K-Correction to the CO Index	57
6	The Color-Magnitude Relations for the Early-Type Galaxies	58
7	The $(V - K)_0$, $(J - K)_0$ Relations for the Early-Type Galaxies	59
8	The $(H - K)_0$, Color Relations of the Early-Type Galaxies	60
9	The CO Index for the Early-type Galaxies	61
10	The H ₂ O Index for the Early-type Galaxies	62
11	The I(7100) Index for the Early-type Galaxies	63
12	The I(7450) Index for the Early-type Galaxies	64
13	The I(7890) Index for the Early-type Galaxies	65
14	The S(7890) Index for the Early-type Galaxies	66

15	The I(8197) Index for the Early-type Galaxies	67
16	The I(8460) Index for the Early-type Galaxies	68
17	The Na I Index for the Early-type Galaxies	69
18	The Mg8807 Index for the Early-type Galaxies	70
19	The Ca8498 Index for the Early-type Galaxies	71
20	The Ca8542 Index for the Early-type Galaxies	72
21	The Ca8662 Index for the Early-type Galaxies	73
22	The Ca II Index for the Early-type Galaxies	74
23	The Relationship Between MK Spectral Type and TiO Band Strength for Field Giants	147
24	The Baade's Window Color-Magnitude Diagram	148
25	Gaussian Fits to the Distribution of Stars in the Baade's Window Color-Magnitude Diagram	149
26	Gaussian Fits to the Distribution of Stars in the Baade's Window Color-Magnitude Diagram	150
27	Characteristics of the Stellar Distribution in the Baade's Window Color- Magnitude Diagram	151
28	Gaussian Fits to the Distribution of Stars in the Baade's Window Color-Magnitude Diagram After Correction for Disk Star Contamination	152
29	A Comparison of the Baade's Window Color-Magnitude Diagram to Isochrones from Vandenberg (1985)	153
30	The Baade's Window <i>I</i> -Band Luminosity Function	154

31	The Baade's Window Calibration Relation Between $(V - I)_0$ and $(H - K)_0$	155
32	The Baade's Window Calibration Relation Between $(H - K)_0$ and $(I - K)_0$	156
33	The Baade's Window Calibration Relation Between $(H - K)_0$ and $(J - H)_0$	157
34	The Baade's Window Calibration Relation Between $(H - K)_0$ and CO	158
35	The Baade's Window Calibration Relation Between $(H - K)_0$ and H ₂ O	159
36	The Baade's Window Calibration Relations Between $(H - K)_0$ and the Molecular Band Indices	160
37	The Field Giant Relations Between $(H - K)_0$ and the Molecular Band Indices	161
38	The Baade's Window Calibration Relations Between $(H - K)_0$ and the Atomic Line Indices	162
39	The Field Giant Relations Between $(H - K)_0$ and the Atomic Line Indices	163
40	The Field Dwarf Relations Between $(H - K)_0$ and the Atomic Line Indices	164
41	The Color-Magnitude Sequence of the Baade's Window Model	165
42	The Photometric Properties of the Baade's Window Models as a Function of $(V - K)_0$	166
43	The Photometric Properties of the Baade's Window Models as a Function of $(J - K)_0$	167
44	The Molecular Band Indices of the Baade's Window Models as a Function of $(V - K)_0$	168

45	The Molecular Band Indices of the Baade's Window Models as a Function of $(J - K)_0$	169
46	The Atomic Line Indices of the Baade's Window Models as a Function of $(V - K)_0$	170
47	The Atomic Line Indices of the Baade's Window Models as a Function of $(J - K)_0$	171
48	The Color-Magnitude Sequences of the Galactic Bulge Models at -6° and -8°	172
49	The Photometric Calibration Relations for the -6° and -8° Fields . . .	173
50	The Molecular Band Index Calibration Relations for the -6° Field . .	174
51	The Molecular Band Index Calibration Relations for the -8° Field . .	175
52	The Atomic Line Index Calibration Relations for the -6° Field	176
53	The Atomic Line Index Calibration Relations for the -8° Field	177
54	The Photometric Properties of the Galactic Bulge Models as a Function of $(V - K)_0$	178
55	The Photometric Properties of the Galactic Bulge Models as a Function of $(J - K)_0$	179
56	The Molecular Band Indices of the Galactic Bulge Models as a Function of $(V - K)_0$	180
57	The Molecular Band Indices of the Galactic Bulge Models as a Function of $(J - K)_0$	181
58	The Atomic Line Indices of the Galactic Bulge Models as a Function of $(V - K)_0$	182

59	The Atomic Line Indices of the Galactic Bulge Models as a Function of $(J - K)_0$	183
60	The Revised Baade's Window Color-Magnitude Diagram	221
61	The Changes in the Integrated Photometry of the Galactic Bulge as a Function of $(V - K)_0$	222
62	The Changes in the Integrated Photometry of the Galactic Bulge as a Function of $(J - K)_0$	223
63	The Changes in the Molecular Band Indices of the Galactic Bulge as a Function of $(V - K)_0$	224
64	The Changes in the Molecular Band Indices of the Galactic Bulge as a Function of $(J - K)_0$	225
65	The Changes in the Atomic Line Indices of the Galactic Bulge as a Function of $(V - K)_0$	226
66	The Changes in the Atomic Line Indices of the Galactic Bulge as a Function of $(J - K)_0$	227
67	Examination of the Na/I(8197) region of the spectrum I	228
68	Examination of the Na/I(8197) region of the spectrum II	229
69	Examination of the Na/I(8197) region of the spectrum III	230

CHAPTER I

INTRODUCTION

Astronomy is the only discipline in which history can be viewed “as it happens.” Due to the great distances to other galaxies and the finite speed of light, we actually see each galaxy as it appeared in the past, at the time that the light which we detect left the galaxy. The further away the galaxy lies, the further back in time we see it. This means that, if we look at galaxies far enough away, we may be able to see them in the process of forming. Unfortunately, today’s technology does not yet allow us to observe the epoch of galaxy formation.

Since the timescale on which a galaxy evolves is many orders of magnitude longer than a human lifetime, neither can we directly track the evolution of any particular galaxy. Instead, if we assume that all galaxies formed at roughly the same time in the past, then we can study the evolution of galaxies by looking at similar types of galaxies at different redshifts. In principle, this sounds relatively easy; in practice, it is quite difficult. Because different types of galaxies exist - elliptical (E), lenticular (S0), spiral, irregular, dwarf, etc. - the main complication involves matching the galaxies at high redshift with their nearby counterparts.

How then do we learn about the formation and evolution of galaxies? One way to do this is to study the stellar populations of the Milky Way. If we can use this

information to characterize the “present-day” stellar populations of nearby galaxies, then we can potentially use our knowledge of stellar evolution to infer the evolutionary history of these galaxies and to predict how they were formed. Alternatively, we can build models of galaxies, evolve them, and see if they produce anything that looks like what we see today. The former approach is particularly relevant to this thesis.

How do galaxy formation and evolution evidence themselves in stellar populations? To understand this, a very basic outline of galaxy formation will suffice. Presumably, most galaxies formed in the early universe from gravitationally collapsing clouds of gas; these primordial clouds consisted primarily of hydrogen and helium. When the density of a given cloud reached some threshold value, a “starburst” was initiated, and a galaxy was born. After about 10^6 years, the massive stars formed in this initial starburst became Type II supernovae, whose explosions enriched the interstellar medium (ISM) with the heavier elements, also known as metals, which are produced through stellar nucleosynthesis. On a somewhat longer timescale ($\sim 10^8$ years), further enrichment of the ISM occurred in the form of Type I supernovae, mass loss from red giants, and planetary nebula formation. Any star formation that occurred after the initial starburst could incorporate the residual gas remaining from the protogalactic cloud and/or the metal-enriched ISM produced by previous generations of stars. In this way, each successive burst of star formation produces stars which are more metal-rich than the existing stellar population. Thus, the current stellar mix of the galaxy holds valuable clues to understanding two of the fundamental properties which influence a galaxy’s evolution and which differentiate present-day galaxies from

one another - the star formation rate (SFR) and the initial mass function (IMF).

The SFR specifies the gas mass converted into stars as a function of time, so it determines the average age and the spread in age of the stellar population. For any given episode of star formation, the IMF gives the number of stars formed as a function of stellar mass. Referring to the scenario described above, it is clear that the IMF and the SFR work together to determine the average metallicity and the spread in metallicity of the stellar population. Thus, by studying the effects of age and metallicity on stellar populations in the Milky Way and applying this knowledge to observations of other galaxies, there is a hope that we can gain a greater insight into the processes of galaxy formation and evolution.

Star clusters have played a major role in this area because each cluster presumably formed as a unit and therefore represents a simple stellar population - a group of coeval stars of similar chemical composition. Comparisons of the observational data for star clusters of differing age and metallicity have been crucial in refining our understanding of stellar evolution and have also made it clear that age and metallicity are the dominant parameters dictating the photometric and spectroscopic characteristics of stellar populations.

One of the great advantages of studying the star clusters and other stellar populations in the Milky Way is the ability to make observations of individual stars. Unfortunately, this is not usually possible in other galaxies because only the most nearby can be resolved into their stellar components. Instead, most galaxies can only be studied in integrated light. E and S0 galaxies, also known as early-type

galaxies, are especially good subjects for such studies because their light is highly spheroid-dominated, which makes their light profiles quite homogeneous. In fact, the similarity of the trends observed in the integrated light of early-type galaxies to those seen among Galactic globular clusters initially led to the conclusion that early-type galaxies were simply “scaled-up” versions of globular clusters (Faber 1973; Frogel *et al.* 1980; Aaronson *et al.* 1978; Burstein 1979). Although this is no longer believed to be the case, integrated photometry and spectroscopy have nevertheless provided interesting glimpses into the stellar populations of E and S0 galaxies.

1.1 Photometry of Early-Type Galaxies

Photometry of early-type galaxies has taken a giant leap from the days of photographic plates, especially with the advent of infrared and two-dimensional detectors. The former has allowed a much more in-depth exploration of cool stellar populations, which are particularly important in E/S0 galaxies, and the latter has aided a more detailed study of the internal structure of galaxies and their light distribution (see *e.g.* Kormendy & Djorgovski 1989, Silva & Elston 1994, and references therein). With respect to early-type galaxies, two of the major findings of integrated photometry have been the discovery of the color-magnitude (CM) relation between galaxies and the detection of radial color gradients within individual galaxies.

1.1.1 The Color-Magnitude Relation

Early-type galaxies exhibit a CM relation in which the more luminous galaxies tend to be redder. Visvanathan & Sandage (1977; hereafter VS) were the first to study

this effect systematically for a large sample of E/S0 galaxies, and they found the CM relation to be universal. Using the measured redshifts to adjust the apparent magnitudes of the galaxies to a common distance, VS showed that early-type galaxies in different galaxy clusters appeared to obey the same CM relation, that field galaxies also agreed with this trend, and that there was no differentiation between the CM relations for E and S0 galaxies. This implied that the stellar populations of early-type galaxies of similar luminosity were fairly uniform and that the CM relation could be used to determine distances to individual galaxies through simple photometric measurements.

However, Burstein (1977), Faber (1977), and Larson *et al.* (1980) all presented evidence that the CM relation was not as universal as VS had claimed. This was supported by Aaronson *et al.* (1981; hereafter APF), who had hoped to increase the sensitivity of the CM effect through the use of an optical-infrared color. They obtained infrared *JHK* photometry of early-type galaxies in the Virgo and Coma clusters, coupled this with optical photometry from the literature, and determined the relative distance between these two clusters through the magnitude offsets of their respective CM relations. Interestingly, they found that the distance inferred by this comparison was dependent upon the color used in the CM relations. This would imply that Coma and Virgo galaxies of similar luminosity contain different stellar populations. Since the relative Virgo-Coma distance inferred from the $u - V$ colors best matched that predicted by the redshift difference of the two clusters, APF concluded that the stellar population differences were mainly evident at infrared wavelengths and

suggested that the Virgo galaxies contained an intermediate-age population of stars which the respective Coma members lacked.

Although it is much more common to expect differences between galaxies in clusters and those in the field because the contrast in the density of the environment in which the galaxies reside is much more dramatic, it is plausible that galaxies of similar luminosity in the Coma and Virgo clusters could differ in their stellar populations because these two clusters are actually quite dissimilar. The Virgo cluster is a typical cluster of galaxies; it contains approximately equal numbers of E, S0 and spiral galaxies, and the cluster does not yet appear to be dynamically relaxed. The Coma cluster, on the other hand, is richer than about 95% of all galaxy clusters, is rich in early-type galaxies, has a concentrated core and has a very symmetric galaxy distribution, thus implying virialization many crossing times ago. The structural and dynamical differences in these two clusters could produce differences in the stellar populations of the member galaxies if environmental influences have played an important role in their formation and/or evolution.

As explained below, the APF result provided the original motivation for this dissertation research. However, Bower *et al.* (1992a, 1992b; hereafter BLE1 and BLE2, respectively) readdressed the Coma/Virgo CM relations by obtaining new optical photometry for E/S0 galaxies in both the Virgo and Coma clusters and new infrared photometry for the Coma galaxies. Their distance estimates from the $U - V$, $V - K$ and $J - K$ CM relations were not significantly different statistically. They supported the universality of the CM relation and claimed that the APF work was

biased by a combination of: (1) systematic differences in the zero points of the Coma and Virgo optical photometry which APF took from the literature; (2) possible errors in the K -band magnitudes of a few of the faintest Coma galaxies (which differed from the BLE measurements); (3) the sample of galaxies used by APF; and (4) the least-squares fitting technique employed by APF to define the CM relations. These conclusions led to an expansion of the scope of this thesis to include a comparison of the stellar population changes occurring along the CM relation to those responsible for radial color gradients within early-type galaxies.

1.1.2 Color Gradients in Early-Type Galaxies

Color gradients in early-type galaxies are generally modest, which makes them difficult to measure accurately with aperture photometry. With the advent of CCDs, however, measuring internal color gradients in E/S0 galaxies is straightforward, and the data show that these galaxies are generally redder in their centers and get progressively bluer with increasing radius. For purely optical or optical-infrared colors, gradients in different colors appear to be correlated (Peletier *et al.* 1990a, 1990b), but the situation is not nearly as clear when near-infrared $J - K$ colors are included (see *e.g.* Silva & Elston 1994).

Overall, the radial color gradients measured for E/S0 galaxies leave two questions still unanswered. First, what characteristic of the stellar population is changing to produce the color gradients? Second, are the same stellar population variations responsible for the gradients in different colors? These questions cannot be fully addressed using only photometry.

1.1.3 Colors and Stellar Populations

What can be said about the stellar populations of early-type galaxies from colors alone? Assuming that the integrated light of E/S0 galaxies is dominated by an old stellar population (as inferred from comparisons to globular cluster trends), then the reddening of colors in brighter galaxies and in the centers of galaxies could be caused by an increase in either the metallicity or the age of the stellar population. Unfortunately, not much more can be learned photometrically. Worthey (1992, 1994) has shown how degenerate the effects of age and metallicity are with respect to color. For a simple stellar population, he has shown that a 30% change in age produces exactly the same change in the integrated colors of the population as a 20% change in metallicity. Thus, colors are useful for detecting stellar population differences, but they are unable to disentangle the competing effects of age and metallicity. Instead, spectroscopy can be used to try to explore more deeply the specific causes of the CM relation and the radial color gradients in early-type galaxies.

1.2 Spectroscopy of Early-Type Galaxies

The key to studying stellar populations using spectroscopy is finding a set of spectral features which are sensitive to specific characteristics of the stellar population - metallicity, temperature or surface gravity. By first searching for such features in stars in the Milky Way, the hope is to then apply this knowledge to the integrated spectra of other galaxies. However, as with colors, integrated spectra of galaxies can be difficult to decompose.

The spectral energy distribution (SED) of a galaxy is influenced by a number of factors. These include: (1) the spectrum is a composite spectrum of the *entire* stellar population and is thus much more difficult to interpret than a stellar spectrum; (2) the velocity dispersion of the stars in a galaxy broadens the spectral features; and (3) the type of stars which contribute to and/or dominate the SED is a function of wavelength.

Still, all of these effects can be understood, often through modelling, and spectroscopy has been extremely useful in decomposing the integrated light of galaxies into its component stellar populations. Most of this work has concentrated on the blue and visual regions of the spectrum, but the general finding has been that spectral features which are sensitive to metallicity are stronger in the centers of early-type galaxies and in the brighter galaxies. While lending support to the belief that the redder colors observed in these two instances occur because the stellar populations are becoming more metal-rich, the issue is far from settled. Even if the color gradients and CM relation are produced by metallicity effects, they need not be caused by the same chemical composition changes. It is usually assumed that the abundances of all of the metals vary together, but this need not be true; selective enrichment of specific elements may play a role and would probably not affect all colors in the same way. These are some of the areas which this dissertation will explore.

1.3 This Dissertation

The original focus of this dissertation was a search for stellar population differences in early-type galaxies of similar luminosity in the Virgo cluster, the Coma cluster and

the field. This was based upon the finding of APF that the CM relations for E/S0 galaxies in the two clusters were not the same. However, BLE1 and BLE2 made the APF result much less certain, and this dissertation was expanded in scope.

Before the BLE1 and BLE2 data had been published, red spectra (6800 - 9200 Å) had been collected to examine the APF conclusions. In this region of the spectrum, cool stars contribute significant absorption features to the integrated light of galaxies. These observations would also allow an examination of the changes in various spectral characteristics as a function of galaxy luminosity, thus addressing the stellar population variations occurring along the CM relation. It was hoped that these data could then also be utilized to study color gradients within the observed galaxies, so that a comparison of radial trends within E/S0 galaxies to the trends exhibited by the galaxy nuclei as a function of luminosity could be made. Unfortunately, the data obtained here were only of sufficient quality to allow the bright, nuclear regions of the observed galaxies to be examined.

However, the integrated light of the bulges of spiral galaxies appears very similar to the integrated light of early-type galaxies in many respects. In fact, Whitford (1978) showed that an integrated spectrum of the Galactic bulge quite closely resembles that of an elliptical galaxy. In addition, the cool stellar population of the Galactic bulge has been extensively studied (see *e.g.* Frogel 1988; Frogel & Whitford 1987; Frogel *et al.* 1990; Terndrup *et al.* 1990, 1991); in particular, Terndrup *et al.* (1990) have obtained red spectra for Galactic bulge M giants at a number of different latitudes. Could these data be used to model the Galactic bulge stellar population radially and

then be used to infer the radial changes occurring within E/S0 galaxies? The belief was a qualified yes, so modelling the Galactic bulge as a function of latitude was included as another portion of this dissertation research.

Thus, this dissertation addresses two questions of importance to the stellar populations of early-type galaxies. First, are there differences in the cool stellar populations of early-type galaxies of similar luminosity in the Coma cluster, the Virgo cluster and the field? Second, are the radial color changes seen within E/S0 galaxies produced by the same types of stellar population variations that cause the CM relations?

The dissertation is structured as follows. Chapter 2 describes the collection of the observational data and the data reduction. Chapter 3 discusses the spectral features measured from the early-type galaxy spectra and how they vary with color and luminosity among the E/S0 galaxies in the Virgo cluster. The Virgo galaxy trends are then compared with the Coma and field galaxy data. In Chapter 4, the Galactic bulge models are described. Chapter 5 is a discussion of the Galactic bulge stellar population and a comparison of the radial gradients observed in the Galactic bulge to the color, spectral feature relations of the Virgo galaxies. Chapter 6 summarizes the major conclusions of this work and suggests some future areas of research.

CHAPTER II

OBSERVATIONS AND DATA REDUCTION

To compare and contrast the cool stellar populations of early-type galaxies in different environments, red (6800 - 9200 Å) and near-infrared (K -band) spectra were obtained for a group of E/S0 galaxies in the Virgo cluster, the Coma cluster and the field. In this chapter, the selection criteria used to assemble the galaxy sample are given. In addition, the photometry and other useful data adopted from the literature is presented for these galaxies, and the acquisition and reduction of the spectroscopy are described.

2.1 The Galaxy Sample

The sample of galaxies to be observed was dictated by the original premise of this thesis, a search for differences in the cool stellar populations of early-type galaxies of similar luminosity in the Virgo cluster, the Coma cluster and the field. The Coma and Virgo galaxies were chosen from the Aaronson *et al.* (1981; hereafter APF) sample in an attempt to span as large a range of their respective color-magnitude relations as possible. Figure 1 reproduces the $u-K$, K diagram from APF (their Figure 2), which was used as a guide in choosing the Virgo and Coma galaxies to observe here; the filled points in the figure show the galaxies for which red and near-infrared spectra

were obtained. The field galaxies, on the other hand, were selected solely by the criterion that they could be observed on the nights of Coma and Virgo observations during times when the Coma and Virgo galaxies were inaccessible.

2.1.1 Data Taken from the Literature

Table 1 presents the galaxy photometry and other information adopted from the literature. Columns 1 and 2 give the galaxy names and morphological types, respectively, the latter being taken from de Vaucouleurs *et al.* (1993; hereafter RC3). Column 3 gives the radial velocity adopted for each galaxy, which is the optical measurement given by RC3. Column 4 presents the central velocity dispersions; all of these values come from Whitmore *et al.* (1985), except those of IC 3998 and IC 4026 (Dressler 1987), NGC 2974 (Davies *et al.* 1987), and NGC 4124 and NGC 2723 (derived as described below).

The *VJHK* photometry listed in columns 5-9 was taken from either Persson *et al.* (1979, hereafter PFA), APF or Bower *et al.* (1992a; hereafter BLE1). In general, the PFA and APF data were preferred because they better represent the area of the galaxy from which the spectral data was extracted, the galaxy nucleus. These authors presented most of their photometry at specific values of $\log[A/D(0)]$, where A is the aperture diameter used for the photometry and $D(0)$ is the the major axis diameter of the galaxy; they used subscripts to denote the $\log[A/D(0)]$ value of their tabulated data. Usually, $V_{-0.3}$ and $K_{-0.3}$ magnitudes and $(V - K)_{-0.6}$, $(J - K)_{-0.6}$ and $(H - K)_{-0.6}$ colors were given; however, for the Coma galaxies the $J - K$ and $H - K$ colors were given instead at a specific aperture diameter ($14.9''$).

Because BLE1 showed that there exist large uncertainties and a systematic offset in the Virgo and Coma zero points for the V -band photometry used by PFA and APF, the $K_{-0.3}$ magnitudes were considered to be more reliable indicators of galaxy luminosity than $V_{-0.3}$; these are given in column 5 of Table 1. The K magnitudes given in column 6, K_{vir} , are the $K_{-0.3}$ magnitudes adjusted to the distance of the Virgo cluster. For the Coma cluster galaxies, a relative distance modulus of 3.60 mag. between the Virgo and Coma clusters has been assumed (Bower *et al.* 1992b; hereafter BLE2); for the field galaxies NGC 2974, NGC 3115 and NGC 3379, K_{vir} was determined from the final estimated distance (in km sec^{-1}) given in column 12 of Table 3 of Faber *et al.* (1989), assuming $H_0 = 75 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ and a distance modulus to the Virgo cluster of 31.25 mag. (calculated from the same Faber *et al.* data). Because NGC 3384 was not observed by Faber *et al.*, its distance was estimated from its radial velocity, assuming a smooth Hubble flow. The error in this distance should lie well within the observational uncertainties; when a similar approximation is used for NGC 3379, which lies very near NGC 3384 on the plane of the sky and has a similar radial velocity, the resulting difference in K_{vir} is only 0.08 mag.

Due to the aforementioned uncertainties in the PFA/APF V -band data, the $V - K$ colors given in column 7 of Table 1 were taken directly from BLE1 whenever possible; BLE1 adjusted their colors to aperture sizes equivalent to $5h^{-1}$ kpc in the Virgo and Coma clusters. A comparison of the data for the 25 Virgo and Coma galaxies observed here for which $V - K$ colors were measured by both BLE1 and PFA gives $\langle \Delta(V - K) \rangle = 0.038 \text{ mag.}$ in the sense PFA - BLE1; when three highly discrepant

galaxies are omitted, the average difference becomes 0.014 mag. Interestingly, although the aperture sizes differ, there appears to be no systematic difference between the $V - K$ colors of BLE1 and PFA; thus, the PFA data were used for those galaxies not observed by BLE1 (NGC 4179, NGC 4754 and all of the field galaxies). Since BLE1 obtained infrared photometry for only the Coma galaxies and found good agreement with the PFA data, the $J - K$ and $H - K$ colors presented in columns 8 and 9 of Table 1 were taken from PFA.

Columns 10 and 11 of Table 1 give the photometric measurements of the $2.3 \mu\text{m}$ CO band and the $1.9 \mu\text{m}$ H_2O band and were taken from Frogel *et al.* (1978) and Aaronson *et al.* (1978), respectively. For better comparison with the CO absorption measured from the K -band spectra, the CO values are those measured in the smallest aperture by Frogel *et al.*. All of the photometry in Table 1 except the CO and H_2O measurements has been corrected for reddening and redshift by the original authors. The uncertainties in the photometric data are given at the bottom of the table and were generally taken from the references cited above; the uncertainty in $K_{-0.3}$ has been revised because the estimate of PFA (± 0.02 mag.) seemed unrealistically low.

2.2 Red Spectroscopy

The spectra of cool stars exhibit strong absorption features between 6000 and 10,000 Å which are also prevalent in the integrated spectra of early-type galaxies. In addition, Galactic bulge giants, which are considered to be close counterparts to the cool stellar populations of E/S0 galaxies have been extensively studied in this wavelength regime (Terndrup *et al.* 1990). For these reasons, red spectra of the early-type galaxies

were considered to be critical to an evaluation of their cool stellar populations. The following sections describe the observations and data reduction required to obtain these spectra.

2.2.1 Observations

The optical spectroscopy was obtained on the nights of 1991 February 1-6, March 9-13, April 7-11, April 24-25, May 8-9 and May 25-27, using the Ohio State University CCD Spectrograph (CCDS) on the 72-inch Perkins Telescope located on Anderson Mesa near Flagstaff, Arizona; all of the observations except those of February 1-6 were performed remotely from Columbus, Ohio. The CCDS is a long-slit (5') Boller & Chivens spectrograph, and at the time of these observations, the CCDS contained a TI 390 x 584 pixel, front-illuminated CCD chip which had been coated for higher quantum efficiency in the ultraviolet; the resulting spatial resolution was $\sim 0.8''$ pixel⁻¹. The spectra of February and March used a 150 l mm⁻¹ grating blazed at 5000 Å in first order, while all later observations used a 158 l mm⁻¹ grating blazed at 8000 Å, also in first order; a red filter was used to block higher order light. The slit width was always 1.7'', producing a 2-pixel spectral resolution of ~ 9 Å with either grating.

Because the CCD response is nonlinear at very low light levels, a preflash mechanism is built into the CCDS. The three LEDs used for this preflash do not evenly illuminate the chip, so bias frames, consisting of zero-second integrations showing only the 20 msec preflash pattern, were taken at the beginning and end of each night. In addition, the CCDS incorporates a quartz lamp for producing flat-field frames,

and quartz flats were also taken at the beginning and end of each night of observing. Twilight sky exposures were acquired nearly every evening in order to correct for variations in the detector response along the slit; only about 3' of the 5' slit length is unvignetted, and there also exists a slope to the detector's response along the slit in the unvignetted region.

Each individual galaxy integration was typically 1200 sec.; for longer exposures, contamination of the spectra by cosmic rays became significant. For all observations along the meridian or at low air masses, the slit was positioned in the N-S direction. Compensation for atmospheric differential refraction was performed by rotating the spectrograph whenever the differential refraction between the red and blue ends of the spectrum was estimated to be greater than 20% of the slit width. Table 1 of Fillippenko (1982) indicated that this occurred at an air mass of about 1.30, so the slit was rotated for all observations at air masses higher than this; Fillippenko's Table 2 was used to determine the proper slit position. This effect was important primarily during the May observing sessions, when the Virgo and Coma galaxies were low in the sky for much of the night. Differential refraction may have also affected the observations through slit misalignments because the spectra were centered near 8000 Å while the centering of the object in the slit was done using a V-band image; no attempt was made to correct for this effect.

Flux standards were observed each night at a range of air masses. Initially, these standards were chosen from the lists of Oke (1974) and Oke & Gunn (1983); in the end, the flux standards HD 19445, HD 84937, BD +26°2606 and BD +17°4708

from Oke & Gunn were preferred. Since these stars are metal-poor subdwarfs, their spectra contain very few spectral lines, so they were also used to monitor the telluric absorption throughout the night. To properly correct the galaxy spectra for telluric contamination, one of these standards should have been observed at the same time and airmass as each early-type galaxy. In reality, the telluric absorption did not appear to vary much with time, so it was considered more critical to acquire standard star observations which spanned the airmasses of the galaxy data.

For wavelength calibration of the spectra, comparison spectra were obtained as needed throughout each night using an Fe-Ne lamp; special attention was paid to those instances in which the telescope position changed enough to suspect that instrumental flexure would alter the wavelength scale of the spectra.

2.2.2 Data Reduction

IRAF was used for all of the spectroscopic data reduction. The first step in this process was the preparation of final bias and flat-field frames for each night. Because the sets of bias frames taken at the beginning and end of a night differed by more than 1% on only three nights, a final bias frame was produced for each night by simply averaging (with sigma-clipping) all of the bias frames taken that night. The final quartz frame was usually produced in exactly the same manner as the final bias frame, except when the quartz frames taken at the beginning and end of the night differed substantially (see below). Next, the slit illumination function was determined from a sum of the individual sky frames taken that night (using the IRAF package “response”). The final flat-field frame was a product of the slit illumination function

and the final quartz flat.

Overall, proper flat-field correction was inhibited by two factors. First, the ultra-violet coating on the CCD chip produced gross features in the quartz frames which made it impossible to correct them for any slope due to the color of the quartz lamp. Instead, these features were presumably removed during flux calibration of the spectra. In addition, post-observation analysis showed that, especially during the last few nights of observations, the flat field frames taken at the beginning of the night often differed from those taken at the end of the night. Closer inspection of data taken throughout each night indicated that these flat-field shifts seemed to coincide with rotations of the spectrograph. Frames taken before the first rotation or after the final rotation on a given night seemed to be properly corrected by normal flat-fielding procedures using only the average early and late quartz frames, respectively, so they were flattened in this manner. However, attempts to flatten the data taken intermediate to the initial and final spectrograph rotations produced much noisier results; apparently, these frames could not be properly flat-fielded. For lack of a better procedure, the average of all quartz flats taken on that specific night was used in producing the final flat-field frames for these data. Unfortunately, it was during these problematic nights that many of the fainter Coma galaxies were observed, so low photon statistics exacerbated the problem.

Before extraction of the spectra, all frames were first overscan-corrected, trimmed (to remove the vignetted portions of the image), bias-subtracted and flattened. Stellar spectra were extracted using an aperture width corresponding to the width of the

spectrum at $\sim 10\%$ of the peak counts; for galaxies, this width was set at $\sim 50\%$ of the peak. Stellar spectra were traced interactively, while the tracings of the galactic spectra assumed the tracing parameters of the stellar observation nearest in telescope position to that of the galaxy. For each stellar or galaxy spectrum, the tracing parameters were then used to extract a comparison spectrum from the Fe-Ne frame nearest in telescope position to that of the object observed. When choosing the trace star to use in the extraction of a galaxy spectrum or the Fe-Ne frame to use for comparison spectra, the slit position angle, the local sidereal time and the hour angle of the trace star and/or Fe-Ne frame were taken into consideration. Often, the average of two Fe-Ne comparison frames were used, especially if they bracketed a set of galaxy integrations. During wavelength calibration, any Fe or Ne lines having residuals greater than $0.5 \text{ \AA}$ were deleted from the fit.

For consistency, flux calibration was performed using only the standards HD 19445, HD 84937, BD +26°2606 and BD +17°4708 of Oke & Gunn (1983). Flux points which overlapped telluric features in the standard star spectra were first deleted. Additional wavelength bands were then defined for each standard star in regions uncontaminated by telluric absorption until a consistent set of wavelength bands was determined for use in flux calibration; this final set of flux calibration points was then used for every night's observation of each standard star.

After flux calibration, three further corrections were applied to the E/S0 galaxy spectra. First, telluric absorption features were removed. Then, the wavelength scales of the spectra were adjusted to zero redshift, using the radial velocities listed

in Table 1. Finally, the spectra were broadened to a common velocity dispersion. Because the telluric absorption corrections and the velocity dispersion corrections are somewhat involved, they are described more fully in the following sections.

Corrections for Telluric Absorption

Whenever possible, the Oke & Gunn (1983) standard stars and HD 122563, a metal-poor K giant, were used to remove telluric absorption features from the galaxy spectra; on one night, it was also necessary to use Wolf 1346, an Oke (1974) standard star, for this purpose. As mentioned above, the Oke & Gunn standards are all extremely metal-poor subdwarfs, so they have very smooth spectra which exhibit only the Ca II triplet ($\lambda\lambda 8498, 8542$ and $8662 \text{ \AA}$) and the telluric absorption features. The stars used for removal of telluric absorption in the galaxy spectra will be referred to as telluric standard stars (TSS).

To correct the galaxy spectra for telluric absorption, a correction spectrum was first constructed from each TSS spectrum. This was accomplished by: (1) fitting a third order cubic spline to selected, uncontaminated continuum regions in each TSS spectrum, (2) dividing the original TSS spectrum by this fit, and (3) interpolating over the Ca II triplet absorption. This left a spectrum which was normalized to near unity in all regions in which there were no major telluric features. Figure 3 shows an example of such a spectrum, which will be referred to as a telluric spectrum; the major telluric features are noted in the figure.

The telluric features were removed from each galaxy spectrum using the telluric spectrum which fell nearest in airmass to the galaxy observation. However, it was noted that simple division of a galaxy spectrum by the chosen telluric spectrum often left large residual “spikes” in the corrected galaxy spectrum due to slight wavelength offsets between the telluric features present in the galaxy and telluric spectra. Thus, proper removal of the telluric features required that the telluric spectrum be shifted in wavelength. To determine the best correction, the following procedure was followed: (1) a series of telluric spectra were constructed by shifting the original telluric spectrum in 0.1 Å increments in wavelength; (2) the galaxy spectrum was divided by each telluric spectrum in the series; (3) the continuum of each corrected galaxy spectrum was fit with a high-order cubic spline; and (4) the standard deviation of the flux in the region of the telluric O₂ A-band (see Figure 3) was determined. In general, this standard deviation showed a smooth variation with the wavelength shift of the telluric spectrum, and the correction which gave the lowest residual for the removal of the O₂ A-band was easily determined. The corrected galaxy spectrum which showed this minimum residual was then used for further reduction and analysis.

Velocity Dispersion Corrections

Any feature observed in the integrated spectrum of a mix of stars is broadened by the velocity dispersion of the stellar populations which contribute to that feature. Thus, to compare the strengths of spectral features in galaxy spectra, all of the data must be adjusted to a common velocity dispersion. This is usually done by applying empirical

corrections to the measurements made from the *observed* spectra or by broadening all of the spectra to a common velocity dispersion (usually the highest in the sample).

The former method involves incrementally broadening the spectrum of a template star and determining the change in feature strength as a function of velocity dispersion. However, the magnitude of the resulting correction can be dependent upon the spectral type of the template star, so a choice must be made with respect to what type of star best represents the “average” stellar population of the “average” galaxy. This method was examined here for the Ca II $\lambda 8542$ line, using Galactic bulge K and M giants as the templates. The resulting corrections showed a scatter of about 0.5 Å for velocity dispersions between 150 and 500 km sec⁻¹; this scatter did not correlate with either color or spectral type of the template star. A wavelength calibration which is uncertain by one pixel was found to produce a scatter of about 0.25 Å.

Because of the large uncertainties in the velocity dispersion corrections predicted by this simulation, it was decided that the latter method mentioned above was preferable. Thus, before spectral feature strengths were measured, the galaxy spectra were convolved with Gaussians in order to broaden them to the velocity dispersion of NGC 4889, the galaxy with the highest velocity dispersion (391 km sec⁻¹) in the sample.

Table 1 gives the central velocity dispersions of the galaxies observed here. Most of these measurements come from either Whitmore *et al.* (1985) or Dressler (1987). However, NGC 4124 and NGC 2723 have not had their central velocity dispersions measured, so it was necessary to estimate these values. For NGC 4124, the central velocity dispersion was estimated from the $K_{-0.3}$ magnitude. Figure 2(a) is a plot

of $\log \sigma_c$ vs. $K_{-0.3}$ for the Virgo galaxies observed by APF with central velocity dispersions measured by Whitmore *et al.* The solid line is a linear least-squares fit to the data and was used to estimate the central velocity dispersion of NGC 4124.

For NGC 2723, $B_{T,0}$, the apparent total B magnitude corrected for extinction, was used to estimate σ_c . Figure 2(b) shows $\log \sigma_c$ vs. $B_{T,0}$ for the Virgo galaxies observed here. The solid line is a linear least-squares fit to the data and was used to find the central velocity dispersion of NGC 2723. To use this relation, the $B_{T,0}$ magnitude for NGC 2723 had to be adjusted to the distance of the Virgo cluster; this was done in exactly the same manner described previously to derive K_{vir} .

2.2.3 Near-Infrared Spectroscopy

Because the CO and H₂O absorption which appears in the K -band is so sensitive to the properties of the cool stellar populations of a galaxy (see Chapter 3), near-infrared K -band spectra were obtained for all but one of the galaxies in the optical sample. The following sections describe the acquisition and reduction of this data.

Observations

The K -band spectra were obtained on the nights of 1992 April 8-13 using the infrared Cryogenic Spectrometer (CRSP) at the f/15 Cassegrain focus of the 2.1-meter telescope at Kitt Peak National Observatory (KPNO). CRSP is a long-slit spectrometer which contains a SBRC 58 x 62 pixel InSb array. This configuration gives a spatial resolution of $1.5'' \text{ pixel}^{-1}$; the $510 \mu\text{m}$ slit used here corresponded to $3.3''$ on the sky and was always positioned in the E-W direction. Grating #2 allowed the entire K

band to be observed in a single exposure at a spectral resolution of ~ 250 ($0.0089 \mu\text{m pixel}^{-1}$).

Dome flats were taken at the beginning of each night of observing. Per the CRSP Observer's Manual (Elston 1990), these flats were taken at six different grating settings using the high-resolution grating (grating #1) in the K band. Dark frames with the same exposure times as the dome flats were also collected.

Observations of early-type galaxies were taken in sets of 12 exposures; each exposure was generally 20-25 seconds, but the integration times were adjusted as necessary to keep the night sky emission at the red end of the K -band within the linear regime of the array. Each set of galaxy observations was bracketed by a set of six similar-length exposures of blank regions of the sky. The first exposure in each sky set was positioned $\sim 4'$ from the corresponding galaxy in a region determined to be free of contaminating objects per finding charts constructed from the Palomar Sky Survey plates. Each of the six sky exposures in a set was taken at a position offset from the previous exposure by $\sim 10''$. Periodic checks made throughout the run indicated that, when a suitable guide star could be located for a given galaxy, reacquisition of the guide star after the sky observations was sufficient to recenter the galaxy on the slit. However, for those galaxies for which guide stars could not be located, the galaxy was "peaked up" after each set of sky integrations.

A-type dwarfs (Elias et al. 1982) were observed for removal of telluric absorption features from the galaxy spectra. For each galaxy, a specific, nearby A star was chosen, and this star was then usually observed before and after each set of observations of the

corresponding galaxy. For these stars, five successive spectra were obtained by simply moving the star approximately 10" along the slit between exposures. In addition, an object known to exhibit *K*-band emission lines, either the Ring Nebula (NGC 6720) or the Orion Nebula (NGC 1976), was observed each night for use in wavelength calibration of the galaxy spectra.

Data Reduction

Before proceeding with the data reduction, it was first necessary to discard some exposures from the nights of April 8-9. These had evidently been corrupted when an attempt was made to access information on the disk on which the observations were stored at the same time that the instrument was trying to write new data to the same disk. Since this problem was discovered during the second night of observing, none of the April 10-13 observations were affected.

IRAF was also used to reduce the infrared spectra. For each night, the dark frames were median-filtered, and the resulting dark frame was subtracted from each flat-field frame. The slope present in each individual dome flat (due to the color of the quartz lamp) was then removed, and the flats were median-filtered; normalization of the resulting image produced a final flat-field frame for that night.

Each set of five stellar exposures were median-filtered to produce a sky frame, which was then subtracted from each individual stellar exposure. The resulting images were flattened, and spectra were then extracted from each, with the aperture width set to the approximate width of the spectrum at $\sim 10\%$ of the peak counts; this

extraction included second-order sky subtraction. The five resulting spectra were median filtered, after scaling the region of maximum flux to a common count level.

For each set of galaxy spectra, a sky frame was produced by averaging all of the exposures in the sets of sky frames directly preceding and following the galaxy observations. For first-order sky subtraction, this average sky frame was subtracted from each of the individual galaxy frames in the set. Each galaxy exposure was then flattened, and the 12 frames in each set were averaged. Next, second-order sky subtraction was performed by median-filtering 11 rows near each edge of the array and subtracting the resulting sky spectrum from each row of the array. Galaxy spectra were then extracted using an aperture width of $\sim 50\%$ of the peak counts in a spectral cross-section. The A star chosen for removal of telluric features was used to guide the tracing of each corresponding galaxy spectrum; in doing this, the A-star spectrum which fell nearest the center of the array was used.

Wavelength calibration was performed through observations of the Orion Nebula and the Ring Nebula. Data for these objects were reduced in exactly the same manner as the galaxy spectra through the point of averaging all of the frames in a set. A series of spectra were then extracted from these frames, using the same extraction parameters used for the star and galaxy spectra to be wavelength calibrated. Emission lines of He I ($2.0581 \mu\text{m}$), H_2 ($2.1218 \mu\text{m}$) and Br γ ($2.1661 \mu\text{m}$) were assigned their known wavelengths in these calibration spectra, which were then used to wavelength calibrate the galaxy and A-star spectra.

Each galaxy spectrum was also corrected for telluric absorption features. After wavelength calibration, the spectrum of the designated A star was divided by a normalized, 10,000 K blackbody spectrum. Then the Br γ absorption in the A star spectrum was removed by interpolation of the continuum on either side of the line. Finally, the A star spectrum was normalized. Division of the galaxy spectrum by this final, normalized A star spectrum removed most of the telluric absorption. After adjusting all of the individual galaxy spectra to zero redshift, a final spectrum was produced for each galaxy by simply averaging all of the fully-corrected spectra of that galaxy.

Table 1: The Early-Type Galaxy Sample

Galaxy	Type ^a	RV ^a	σ_c^b	$K_{-0.3}^c$	K_{Vir}^d	$(V-K)_0^e$	$(J-K)_0^f$	$(H-K)_0^g$	CO ^g	H ₂ O ^h
Virgo Galaxies										
NGC 4124	SA(r)0+	1631	128	8.82	8.82	2.94	0.80	0.17	...	...
NGC 4179	S0sp	1256	164	7.90	7.90	3.32	0.89	0.23	...	...
NGC 4374	E1	1029	296	6.50	6.50	3.28	0.91	0.23	0.150	0.110
NGC 4377	SA0-	1358	136	8.99	8.99	3.09	0.82	0.20	...	...
NGC 4382	SA(s)0+pec	722	200	6.59	6.59	3.07	0.85	0.21	0.130	0.110
NGC 4387	E	561	111	9.42	9.42	3.08	0.81	0.21	...	...
NGC 4406	E3	-248	256	6.51	6.51	3.25	0.87	0.22	0.150	0.115
NGC 4435	SB(s)0	781	171	7.56	7.56	3.55	1.01	0.28	...	...
NGC 4442	SB(s)0	530	217	7.26	7.26	3.24	0.88	0.22	...	...
NGC 4468	SA0-?	895	77	10.58	10.58	2.94	0.85	0.23	...	...
NGC 4472	E2	983	315	5.70	5.70	3.32	0.90	0.21	0.160	0.120
NGC 4478	E2	1382	144	8.43	8.43	3.13	0.84	0.21	0.120	0.125
NGC 4486	cD E0+pec	1282	335	6.08	6.08	3.34	0.94	0.22	0.150	0.125
NGC 4552	E	311	273	6.90	6.90	3.33	0.93	0.25	...	...
NGC 4636	E0+	927	217	6.99	6.99	3.21	0.92	0.23	...	...
NGC 4660	E:	1095	196	7.97	7.97	3.14	0.85	0.22	...	...
NGC 4754	SB(r)0-:	1396	204	7.45	7.45	3.29	0.84	0.22	...	...
Coma Galaxies										
NGC 4874	cD E0	7152	262	9.62	6.02	3.25	0.93	0.23	...	...
NGC 4881	cD	6705	193	10.79	7.19	3.19	0.89	0.19	...	...
NGC 4886	E0	6345	155	11.45	7.85	3.03	0.87	0.17	...	...
NGC 4889	cD E4	6494	391	8.84	5.24	3.35	0.96	0.22	0.080	0.125
NGC 4906	E3	7471	166	11.34	7.74	3.14	0.86	0.19	...	...
NGC 4923	(R')SA(r)0-	5455	192	10.70	7.10	3.14	0.85	0.19	...	...
IC 3998	SB0	9388	156	11.55	7.95	3.22	0.86	0.20	...	...
IC 4011	E	7209	104	12.52	8.92	3.04	0.87	0.22	...	...
IC 4012	E	7221	181	11.94	8.34	3.24	0.93	0.21	...	...
IC 4026	SB0	8137	140	11.76	8.16	2.99	0.93	0.19	...	...
Field Galaxies										
NGC 2723	S0:	3725	168	...	...	...	...	...	...	...
NGC 2872	E2	3014	297	...	...	...	...	...	...	...
NGC 2974	E4	2006	222	8.01	6.66	3.30	0.86	0.17	0.130	0.135
NGC 3115	S0-sp	670	247	5.98	6.56	3.30	0.87	0.21	0.150	0.135
NGC 3156	S0:	1118	141	...	...	...	...	...	...	...
NGC 3379	E1	889	218	6.48	7.44	3.30	0.87	0.19	0.140	0.110
NGC 3384	SB(s)0-:	735	173	7.07	8.36	3.18	0.82	0.18	0.150	0.100
Photometric Uncertainties										
				0.10	0.20	0.03	0.04	0.03	0.02	0.02

^amorphological types and radial velocities (in km sec⁻¹) from de Vaucouleurs *et al.* (1993)^bcentral velocity dispersions (in km sec⁻¹) from Whitmore *et al.* (1985), Dressler (1987) or Davies *et al.* (1987)^cphotometry from Persson *et al.* (1979) or Aaronson *et al.* (1981)^d $K_{-0.3}$ magnitudes adjusted to the distance of the Virgo cluster as described in the text^ephotometry from Bower *et al.* (1992a) or Persson *et al.* (1979)^fphotometry from Persson *et al.* (1979)^gphotometry from Frogel *et al.* (1978)^hphotometry from Aaronson *et al.* (1978)

Figure 1: The selection of the galaxy sample. The $u - K$, K color-magnitude diagram for the Virgo and Coma E/S0 galaxies observed by Aaronson *et al.* (1981) is reproduced (their Figure 2). The solid lines are the color-magnitude relations derived by Aaronson *et al.* The Coma galaxies are represented by triangles, the Virgo galaxies are shown as circles, and the early-type galaxies observed here are shown as the filled points.

Figure 2: Estimation of the central velocity dispersions of NGC 4124 and NGC 2723. (a) the central velocity dispersion (σ_c) of NGC 4124 is estimated. $\log \sigma_c$ (Whitmore *et al.* 1985) is plotted *vs.* $K_{-0.3}$ for all of the Virgo galaxies observed by Aaronson *et al.* (1981). The solid line represents a linear least-squares fit to the filled points and has been used to derive σ_c for NGC 4124. (b) the central velocity dispersion of NGC 2723 is estimated. $\log \sigma_c$ (Whitmore *et al.*) is plotted *vs.* $B_{T,0}$ (de Vaucouleurs *et al.* 1993) for the Virgo galaxies observed here. The solid line represents a linear least-squares fit to the filled points and has been used to derive σ_c for NGC 2723.

Figure 3: A sample telluric correction spectrum. The major telluric absorption features are labelled. The dotted line is drawn at a normalized flux of unity.

CHAPTER III

RED SPECTRAL FEATURES IN EARLY-TYPE GALAXIES

The integrated spectra of early-type galaxies contain a wealth of spectral features, both atomic lines and molecular bands. Several of these features have been found to be good indicators of specific characteristics of stellar populations. In this chapter, a few such features are discussed, emphasizing their utility with respect to stellar population studies, and indices are defined which have been used to measure the strengths of these spectral features. Then, the behavior of these indices with color and luminosity is examined for the early-type galaxies in the Virgo cluster. A comparison is made to the Coma cluster and field E/S0 galaxies to determine if galaxies of similar luminosity in the three environments have detectable differences in their cool stellar populations.

3.1 Red Spectral Features in Stars

To use integrated spectra to learn about the stellar populations of a galaxy, it is necessary to understand which spectral features are sensitive to the specific characteristics of the stars producing them. Much previous work has been based upon a search for such potentially important diagnostics, concentrating upon stars in the

Milky Way which have known surface gravities, effective temperatures and metallicities. A variety of spectral indices have been defined in the literature which measure the strengths of specific atomic lines and molecular bands, and the behavior of these indices as a function of basic stellar properties has been examined. In the following sections, the most important of these features which lie in the red or the near-infrared are discussed.

3.1.1 Atomic Lines

In the red region of the spectrum, the best-studied atomic lines are the Ca II triplet at $\lambda\lambda 8498, 8542, 8662 \text{ \AA}$ and the Na I doublet at $\lambda\lambda 8183, 8195 \text{ \AA}$. Each has been found to have good sensitivity to specific stellar properties, as discussed below. In addition, the Mg I $\lambda 8807 \text{ \AA}$ line, while less well-understood, shows some potential for use as a population diagnostic.

The Ca II Triplet

The Ca II triplet has been extensively studied in individual stars in an attempt to determine its sensitivity to surface gravity, effective temperature and metallicity. Since the triplet lies in a region of the spectrum which is uncontaminated by any telluric absorption features, it can be more easily and more reproducibly measured than some other red spectral features. For cool stars, however, care must be taken to avoid contamination of the measurements by the TiO band which overlays the region of the spectrum in which the Ca II lines lie.

The behavior of the Ca II triplet has been examined by Cohen (1978; hereafter C78), Jones *et al.* (1984; hereafter JAJ), Carter *et al.* (1986; hereafter CVP), Diaz *et al.* (1989; hereafter DTT) and Bica & Alloin (1989; hereafter BA) in field stars. In addition, Armadroff & Zinn (1988) measured the strength of the Ca II triplet in the integrated spectra of 27 Galactic globular clusters. In most of these studies, the strength of each line in the triplet was measured separately and a sum of all three line strengths was used to form a Ca index; DTT instead summed only the two reddest lines to produce their index, which they designated Ca II.

Unfortunately, none of the aforementioned studies used stellar samples which spanned a wide range of effective temperature, metallicity *and* surface gravity. Overall, the sample of stars observed by DTT was the most complete in its coverage of surface gravity and metallicity space. In addition, the continuum they used to measure Ca II was defined in a manner which minimized contamination by TiO. Their Ca II index was found to have a biparametric behavior, with 97% of its variation due to changes in $\log g$ and $[\text{Fe}/\text{H}]$; it was stronger in lower gravity and more metal-rich stars, but no dependence on T_e was found. DTT also showed that, for metallicities of about one-half solar and greater ($[\text{Fe}/\text{H}] > -0.3$), the Ca II index is dominated by surface gravity effects, while at lower metallicities, it is strictly a function of $[\text{Fe}/\text{H}]$. Naturally, when they considered giant stars only, metallicity and the Ca II index were correlated.

The trends found by DTT were consistent with the findings of all of the other (less comprehensive) studies mentioned above. Most of these groups found the Ca II triplet

to be a good indicator of surface gravity, being stronger in giants than in dwarfs of the same effective temperature; the metallicity effects were not generally seen because the stars observed were all of approximately solar metallicity. Armandroff & Zinn (1988) noticed only the metallicity dependence for their globular cluster sample because these objects are generally metal-poor and have giant-dominated integrated spectra.

The major shortcoming of the DTT study was the lack of M stars in their sample, which only extended as cool as spectral type M1. C78 observed M stars only and found that the Ca II lines weakened as $(V - K)_0$ got redder but were always stronger in giants than in dwarfs of the same color. The decreasing Ca II absorption in M stars was also evident in the data of CVP but was masked in the JAJ measurements because their continuum bands were so widely separated that they actually measured Ca II + TiO absorption. In fact, these trends are consistent with simple expectations. At some point, the Ca II lines *must* show a dependence upon effective temperature because: (1) they are produced by ionized Ca, which will revert to a neutral state over some range of temperature, and (2) as T_e decreases, TiO absorption increases and the *measured* line strengths will weaken as TiO “eats away” the continuum used to measure the Ca II index. Overall, the use of the Ca II triplet as a population diagnostic is seriously complicated by these temperature effects.

Na I Doublet

The Na I doublet is a well-known indicator of surface gravity in late-type stars, being much stronger in M dwarfs than in giants of similar spectral type and increasing in

strength with later spectral type in M dwarfs (Sharpless 1956). This behavior has been verified more quantitatively by Spinrad (1966), O'Connell (1973), C78 and Faber & French (1980). CVP also attempted to assess the Na I doublet; however, at a velocity dispersion of 250 km sec^{-1} (to which they had broadened their spectra), this feature was blended with a nearby TiO band. Thus, they measured the combined TiO/Na feature and then applied a correction, based upon the strength of another TiO band, to attempt to remove the TiO contamination. Even without this correction, however, it was evident that the Na/TiO feature was much stronger in K and M dwarfs than in giants of the same spectral type. No known dependence of Na I line strength on metallicity has been reported in the literature.

Unfortunately, there are some complications which must be considered when determining how to best measure the Na I doublet. First, these lines lie within a telluric H_2O band, so the observations require a careful correction before a Na I index can be measured. Second, the reddest of the Na I lines can become contaminated by other nearby spectral features (BA, Xu *et al.* 1989). As discussed later (see Section 5.2.2), these and other problems can greatly inhibit the use of the Na I doublet in population studies.

Mg I $\lambda 8807$

DTT is the only study known to have examined the Mg I $\lambda 8807$ line. They found that the Mg I index depends upon effective temperature and metallicity, but no surface gravity effects are evident. The dependence is in the sense that the Mg I line is

stronger at higher metallicities and at lower effective temperatures. However, for $[\text{Fe}/\text{H}] < -0.3$, the Mg I line strength is dominated by metallicity effects and becomes relatively insensitive to T_e .

3.1.2 Molecular Bands

The formation of molecules in the atmosphere of a star is largely dictated by the chemical abundances of the elements and the effective temperature of the star. In general, cooler stars contain more molecules (and hence more molecular absorption) because, at higher temperatures, a greater percentage of the molecules are dissociated into their constituent atomic species. Thus, molecular absorption bands are natural tracers of the characteristics of cool stars. Especially prevalent at red wavelengths are the TiO bands in M stars; in the near-infrared, absorption due to CO and H₂O are strong and have been thoroughly studied.

TiO Bands

The TiO bands are mainly sensitive to temperature, being the primary criterion used to classify M stars. In general, for a given TiO band, absorption first appears at a specific temperature, rapidly increases in strength in cooler stars and then approximately levels off, perhaps due to saturation of the band (CVP, C78, O'Connell 1974, Terndrup *et al.* 1990). The trends exhibited by Galactic bulge stars (see Chapter 4) indicate that bluer TiO bands appear at earlier spectral types and have a greater maximum absorption than the redder bands. In addition, the TiO bands are probably affected by chemical composition (see Terndrup *et al.* 1990 and Chapter 4), being

stronger in more metal-rich stars.

CO and H₂O Bands

Baldwin *et al.* (1973) demonstrated that the near-infrared CO and H₂O bands can be used to discriminate between giants and dwarfs of the same color or spectral type. The specific behavior of these bands with color in cool stars of solar metallicity is presented quantitatively by Frogel *et al.* (1978) and Aaronson *et al.* (1978a). In general, H₂O absorption is not seen in hot stars, sets in near spectral type M0, is greater in dwarfs than in giants for spectral types M0 to M6 and then increases rapidly in giants of later spectral type. In contrast to this trend, the photometric CO index is stronger in giants than in dwarfs at all colors. CO is approximately constant in dwarf stars, while it increases rapidly with decreasing effective temperature in giants with spectral types later than G5. In star clusters, the CO absorption in giants of a specific color is also found to increase with increasing metallicity (Frogel *et al.* 1983, Houdashelt *et al.* 1992).

3.2 Measurement of Spectral Features in Galaxies

To examine the stellar populations of the early-type galaxies observed here, a selection of atomic lines and molecular bands were chosen for analysis. The atomic lines included the (unresolved) Na I doublet at $\lambda\lambda 8183, 8195 \text{ \AA}$, each of the three components of the Ca II triplet at $\lambda\lambda 8498, 8542, 8662 \text{ \AA}$ and the Mg I line at $8807 \text{ \AA}$. The molecular bands consisted of TiO bands with bandheads at $\lambda\lambda 7055, 7666, \text{ and } 8420 \text{ \AA}$ (Turnshek *et al.* 1985), the VO band with bandhead at $7400 \text{ \AA}$ (Turnshek *et*

al. 1985), and the near-infrared CO band with bandhead at $2.29\ \mu\text{m}$ (Baldwin *et al.* 1973). This section describes specifically how the strengths of these features were measured from the red and near-infrared spectra.

3.2.1 Definitions of the Indices

To estimate the strengths of the features listed above, spectral indices were used which had previously been defined in the literature. In general, a spectral index is defined by specifying three wavelength bandpasses used in its measurement - a feature band and two continuum side-bands. To measure the index, a continuum level is first estimated from an interpolation or an extrapolation of the flux in the two continuum bands. Because the true continuum level is sometimes difficult to determine (and may not actually be present in the red spectra of many galaxies; see Bica & Alloin 1987), the continuum level estimated from these side-bands is usually referred to as the pseudo-continuum. The strength of the spectral feature is determined through a comparison of the observed flux within the feature bandpass to the estimated pseudo-continuum level there. In general, atomic line strengths are measured as equivalent widths and given in Å; because a pseudo-continuum (rather than the “true” continuum) is used, these widths are often called pseudo-equivalent widths. Molecular band indices are usually specified in magnitudes of absorption.

Table 2 lists the spectral indices measured from the spectra of the early-type galaxies observed here; this table gives the feature and continuum bandpasses used to measure the indices and the sources in which these indices were originally defined. The atomic line indices were taken from Faber & French (1980) for the Na I doublet,

from Deslisle & Hardy (1992) for the Ca II triplet and from DTT for the Mg I line; Deslisle & Hardy present an excellent discussion of the care which must be taken in choosing the feature and continuum bandpasses for the Na and Ca lines in order to minimize the contamination of the line strength measurements by the overlying TiO bands. For the TiO and VO bands, the I(7100), I(7450), I(7890), S(7890), I(8197) and I(8460) indices of Terndrup *et al.* (1990) were used. Figure 4 presents the red spectral index definitions visually in conjunction with the observed spectrum of NGC 3115.

In the near-infrared, the $2.3\ \mu\text{m}$ CO band strength was measured from the *K*-band spectra. To compare the strength of this band to published narrow-band CO photometry, the CO absorption was estimated through a simple ratio of the flux in two bandpasses, converted to magnitudes of absorption and then normalized such that $\text{CO} = 0.0$ for an A0 star ($T_e = 10,000\ \text{K}$). The bandpasses used to measure the CO index are also given in Table 2; they represent the estimated widths of top-hat filters having the same total transmission as the standard CTIO filters (Cohen *et al.* 1978), which have been assumed to have Gaussian transmission profiles. In determining these bandpasses, the *K*-band continuum filter was assumed to have a central transmission of 90% and a FWHM of $0.11\ \mu\text{m}$; the corresponding values used for the CO filter were 65% and $0.08\ \mu\text{m}$, respectively (Briley 1993).

3.2.2 Measurement of the Indices

All spectral feature measurements were made using the software package *LINER*, an interactive line-fitting routine written at The Ohio State University (Pogge 1995). As described above, the atomic line indices were measured as pseudo-equivalent widths

and are given in $\text{\AA}$; the molecular bands were measured in magnitudes of absorption with respect to the pseudo-continuum. For all measurements, *LINER* estimated the pseudo-continuum in the feature bandpass through a linear fit to the individual pixel fluxes in the continuum sidebands, taking into account the contributions from fractional pixels at the edges of these bands. Pseudo-equivalent widths were determined by fitting a Gaussian to the line profiles, while molecular band absorption was a simple ratio of the observed flux to the estimated pseudo-continuum level within the feature bandpass, converted to magnitudes of absorption.

Table 3 presents the measurements of the atomic line pseudo-equivalent widths for the early-type galaxies observed here. Column 1 gives the galaxy name, and columns 2-13 give the atomic line indices and their associated uncertainties. Ca II (column 12) is the sum of Ca8542 and Ca8662, the two strongest lines of the Ca II triplet. The uncertainties in the indices were estimated as follows: (1) the statistical uncertainty of the mean pseudo-equivalent width was determined for each Virgo E/S0 galaxy with multiple observations; (2) the average uncertainty was calculated for these galaxies; and (3) this average uncertainty was considered to be the *minimum* uncertainty and was assigned to all index measurements of galaxies observed only once and to those indices having estimated uncertainties less than 1σ above this minimum uncertainty.

Table 4 is a compilation of the TiO and VO molecular band strengths for the Virgo, Coma and field E/S0 galaxies. Column 1 again is the galaxy name, and columns 2 through 13 give the molecular band indices and their uncertainties; these uncertainties were determined in exactly the same manner as the atomic line index

uncertainties.

Table 5 gives various measurements of the near-infrared CO band at $2.3 \mu\text{m}$. Columns 1 and 2 of this table give the galaxy names and redshifts; the latter quantities have been derived from the radial velocities listed in Table 1. Columns 3 and 4 give CO_{obs} and its estimated uncertainty, respectively, where CO_{obs} is the CO index measured from the *observed* spectrum; columns 5 and 6 specify the same measurements made from the redshift-corrected spectra. The uncertainties in CO_{obs} and CO were determined as described above for the uncertainties in the other indices. The difference in these two CO indices, in the sense $\text{CO} - \text{CO}_{obs}$, is designated $\Delta(\text{CO})$ and is listed in column 7 of Table 5; column 8 is the uncertainty in $\Delta(\text{CO})$ calculated from the uncertainties in CO_{obs} and CO.

The CO measurements given in column 3 of Table 5 have been used to put the spectroscopic CO indices onto the CTIO system (Cohen *et al.* 1978). For the ten galaxies with both photometric CO measurements (Table 1) and spectroscopic CO indices, the average difference (in the sense spectroscopic CO - photometric CO) is 0.027 ± 0.019 mag. Since the estimated uncertainty in a photometric CO measurement is generally 0.02 mag. or greater, this difference is not considered significant; thus, the spectroscopic CO indices reported in Table 5 are considered to be on the CTIO system.

3.2.3 K-Corrections to CO Photometry

One of the goals of collecting *K*-band spectra of these galaxies was to examine the *K*-corrections to the photometric measurement of the $2.3 \mu\text{m}$ CO band. Frogel *et al.*

(1978) attempted to determine this correction factor from a simple linear fit to CO as a function of redshift for the intrinsically brightest galaxies which they observed. They found a good fit to their data for $K_{CO} = +4.8z$, but they had measured CO for very few galaxies with $z > 0.01$. Using the spectroscopy presented here, a more definitive determination of this K-correction is possible.

Figure 5 shows how the CO band strength changes with redshift for the galaxies observed here; the ordinate, $\Delta(\text{CO})$, is the difference between the CO band measurements from the observed and redshift-corrected spectra and is taken from Table 5. The solid line shown in the diagram is a linear least-squares fit to the data; this fit assumes that $\Delta(\text{CO})$ is the dependent variable and z is the independent variable and considers the uncertainties in $\Delta(\text{CO})$ only. The intercept of the fit is $-0.003 (\pm 0.003)$ mag. and the slope of this relation gives

$$K_{CO} = 5.23(\pm 0.37)z, \quad (1)$$

which is in good agreement with the value derived by Frogel *et al.* (1978).

Because there is a slight hint that the true relation in Figure 5 may become non-linear near the redshift of the Coma cluster, two other least-squares fits were made to the $\Delta(\text{CO})$, z data. A linear fit to only the Virgo and field galaxies has an intercept of $0.002 (\pm 0.002)$ mag. and a slope which gives

$$K_{CO} = 3.71(\pm 0.43)z, \quad (2)$$

while a quadratic fit to all of the data gives

$$K_{CO} = 3.80(\pm 1.68)z + 59.36(\pm 67.87)z^2. \quad (3)$$

The latter two results are reported only for completeness. In general, the linear fit to all of the data is to be preferred.

3.3 Trends in Early-Type Galaxy Nuclei

Now that the spectral indices have been measured for the sample of early-type galaxies observed here, an examination can be made of how these features behave as a function of the luminosity and color of the parent galaxy nucleus. After quantifying the luminosity-index and color-index relationships for the Virgo galaxies, a statistical comparison can be made with the Coma cluster and field galaxies to search for systematic differences among E/S0 galaxies of similar luminosity in these three environments.

3.3.1 The Virgo Galaxies

In this section, the photometry (see Table 1) and spectral indices of the Virgo galaxies are examined as functions of $K_{-0.3}$, $(V - K)_o$ and $(J - K)_o$. In this analysis and throughout the remainder of this dissertation, CO will refer to the CO band strengths measured from the redshift-corrected near-infrared spectra, unless otherwise noted. However, before discussing the galaxy measurements, a general description of the features common to all of the remaining figures in this chapter is warranted.

The behavior of the E/S0 galaxy colors and spectral indices have been quantified through linear least-squares fits to the data, assuming that either $K_{-0.3}$, $(V - K)_o$ or $(J - K)_o$ is the independent variable, in that order of preference, and considering the uncertainties in the dependent variable only. The resulting linear relations are given

in Table 6 and are shown as heavy lines in the figures. The dotted curves shown in the figures are the 99% confidence limits on $\hat{y}$, the value of the dependent variable predicted by the linear least-squares fit.

Columns 1 and 2 of Table 6 give the independent and dependent variables, respectively. The next four columns present the intercept and slope of the linear least-squares fit and their standard errors. Column 7 is the linear least-squares correlation coefficient, and column 8 gives a measure of the significance of the correlation. Here, any fits having $p > 99\%$ are considered to be significant.

In performing the least-squares fitting, the data for the S0 galaxies NGC 4382 and NGC 4435 have been omitted. Initially, the fits included all 17 of the Virgo galaxies observed here, but an examination of the residuals from these fits showed that NGC 4382 and NGC 4435 deviated from the resulting linear trends by $\sim 2\sigma$, *on average*. The average residuals of the other Virgo galaxies followed an approximately Gaussian distribution which was centered near 1.0σ , and all of these galaxies had an average residual of $0.5 - 1.5\sigma$. For this reason, the final fits reported in Table 6 do not include NGC 4382 and NGC 4435.

In most of the figures (Figure 6 is the exception), the top panels present the data for the Virgo galaxies and the heavy, solid lines show the results of the least-squares fitting described above. In the bottom panels of these figures, similar plots present the analogous Coma and field galaxy data. However, the lines shown in the Coma/field galaxy panels are *NOT* fits to this data; they are simply reproductions of the Virgo galaxy fits to be used for comparing the distributions of the two groups of galaxies.

Figure 6 shows the color-magnitude relations of the E/S0 galaxies; in this figure, the Virgo galaxy data is shown in the left-hand panels, and the Coma and field galaxy data is seen in the right-hand panels. Recall that the Coma and field galaxy luminosities have been adjusted to the distance of the Virgo cluster. As expected, the $(V - K)_0$ and $(J - K)_0$ colors redden with increasing luminosity among the Virgo galaxies; however, any trends in $(H - K)_0$ are masked by the small range in this color in relation to its measurement uncertainties. Overall, the Coma and field galaxies follow the Virgo color-magnitude relations quite well; at a given luminosity, the Coma and field E/S0 galaxies may tend to be slightly bluer, on average, than those in the Virgo cluster, but this color difference is not statistically significant.

The $VJHK$ color-color relations are presented in Figures 7 and 8. Table 6 shows that the $(V - K)_0$ and $(J - K)_0$ colors are highly correlated for the Virgo galaxies; in general, the Coma and field galaxies in Figure 7 follow this same trend. $(H - K)_0$ is also seen to redden with both $(V - K)_0$ and $(J - K)_0$ (Figure 8); again, the Coma and field galaxies tend to lie to the blue of the Virgo trends in $(H - K)_0$ in these figures, but the deviations, while systematic, are consistent with the observational errors.

The index-color and index-luminosity trends are shown in Figures 9 through 22. In general, all of the spectral indices tend to behave similarly with increasing luminosity and redder $(V - K)_0$ and $(J - K)_0$ colors. Because the $(H - K)_0$ colors span such a small range of values in comparison to the observational uncertainties, they will not be discussed further. If only the linear relations which are correlated at greater than 99% confidence are considered to be significant (see Table 6), then the following

conclusions apply:

1. The CO index is progressively stronger in brighter and redder galaxies.
2. All of the TiO bands except I(8460) get stronger with increasing luminosity and redder $(V - K)_0$ colors. The behavior of the I(8460) index probably differs from that of the other TiO bands because I(8460) typically has higher measurement uncertainties than the other TiO bands and is also the weakest of the TiO bands measured here, since it does not appear in stars hotter than spectral type M2. The TiO bands may correlate less strongly with $(J - K)_0$ because: (1) this color has a lesser sensitivity to TiO absorption (see Chapter 5), or (2) this color spans a smaller range in color than $(V - K)_0$ does.
3. The pseudo-equivalent width of the Na I doublet definitely increases with luminosity and color. This result is consistent with that seen by Delisle & Hardy (1992) but is much more firmly established here, due to the larger sample of galaxies examined. Although Delisle & Hardy interpret this trend as an indication that the Na I feature is affected by metallicity (as well as the dwarf-to-giant ratio), an interpretation of this feature is extremely complicated (see Chapter 5).
4. The I(7450) measurements indicate that VO absorption has not been detected in any of the galaxies observed. Since this band is only prevalent in stars of spectral type M7 and later, it would be measurable only if the integrated light of a galaxy contains a significant contribution from VERY late-type stars; this

does not appear to be the case for any of the galaxies observed here.

5. The strengths of the Mg I $\lambda 8807$ line and each of the Ca II lines is approximately constant among the galaxies observed. Qualitatively, there may be a tendency for Mg I to be weaker in the Coma galaxies.

Overall, given the sensitivities of the various spectral indices to surface gravity, effective temperature and metallicity (see Section 3.1), the trends exhibited by the Virgo E/S0 galaxies are most consistent with the following scenario: the integrated light of each of the early-type Virgo galaxies observed here is dominated by giant stars having an average $[\text{Fe}/\text{H}] > -0.3$, but the chemical composition of this population changes (either the overall metallicity increases or specific elements are selectively enriched) with redder colors and increasing luminosity.

3.4 Comparison of the Virgo, Coma and Field Galaxies

Since the red and near-infrared spectra of the Coma galaxies generally had much lower signal-to-noise ratios than the Virgo galaxy data, the spectral index measurements tend to have much higher uncertainties for the Coma galaxies and show a much larger scatter in Figures 6 through 22. Because this scatter would probably hide all but the most significant trends in the Coma galaxies, no attempt was made to fit linear relations to the Coma galaxy data alone.

The observed scatter also seriously inhibits the detection of any differences between the colors and/or spectral indices of the Coma and Virgo E/S0 galaxies of similar luminosity. Simply inspecting the figures by eye, it is fairly clear that, within

the measurement uncertainties, the Coma galaxies as a group do not follow significantly different trends than the Virgo galaxies; possible exceptions to this rule occur for the $(H - K)_0$ colors and the Mg8807 indices.

To test this statistically, a two-sample test for independent samples with unequal variances was used (see *e.g.* Rosner 1986). This is a t -test which tests the hypothesis: the variance of the Coma galaxy data (with respect to its measurement uncertainties) about the linear least-squares fits is the same as the variance of the Virgo galaxies about these lines. Here, if the t -test indicates that this hypothesis can be rejected at 99% confidence or higher, then the Coma and Virgo galaxies are considered to follow different trends. Using such a criterion, the Coma galaxy colors and spectral indices are consistent with the Virgo galaxy trends in all of the figures. Any differences between the Coma and Virgo early-type galaxies of similar luminosity cannot be detected with the data presented here.

A similar comparison between the early-type galaxies in the Virgo cluster and those in the field was not attempted because infrared photometry could be located for only four of the field galaxies observed here. In general, however, the field galaxies do not appear unusual in Figures 6 - 22.

Table 2: The Spectral Indices

Index	Feature Bandpass	Blue Continuum Bandpass	Red Continuum Bandpass
Atomic Lines			
Na I ^a	8172 - 8210	8164 - 8174	8208 - 8213
Ca8498 ^b	8483 - 8511	8559 - 8634	8683 - 8758
Ca8542 ^b	8517 - 8559	8559 - 8634	8683 - 8758
Ca8662 ^b	8634 - 8683	8559 - 8634	8683 - 8758
Mg8807 ^c	8799.5 - 8814.5	8775 - 8787	8845 - 8855
Molecular Bands			
I(7100) ^d	7070 - 7130	6990 - 7040	7300 - 7350
I(7450) ^d	7430 - 7470	7300 - 7350	7500.5 - 7575.5
I(7890) ^d	7860 - 7920	7500.5 - 7575.5	8150 - 8180
S(7890) ^d	7860 - 7920	...	8150 - 8180
I(8197) ^d	8179.5 - 8214.5	8150 - 8180	8220 - 8260
I(8460) ^d	8440 - 8480	8395 - 8425	8810 - 8850
CO ^e	2.317 - 2.403	2.141 - 2.259	...

^aFaber & French (1980)^bDelisle & Hardy (1992)^cDiaz *et al.* (1989)^dTerndrup *et al.* (1990)^ederived from CTIO filter transmission functions (see text)

Table 3: The Atomic Line Index Measurements^a

Galaxy	Na I	σ	Mg8807	σ	Ca8498	σ	Ca8542	σ	Ca8662	σ	Ca II	σ
Virgo Galaxies												
NGC 4124	0.28	0.20	0.27	0.15	0.36	0.25	2.80	0.46	2.58	0.38	5.37	0.61
NGC 4179	0.57	0.11	0.49	0.20	0.08	0.45	2.53	0.38	1.95	0.18	4.47	0.41
NGC 4374	0.41	0.11	0.38	0.09	0.30	0.25	2.48	0.29	1.59	0.18	4.08	0.41
NGC 4377	0.10	0.11	0.33	0.09	0.26	0.25	2.70	0.29	1.94	0.18	4.64	0.41
NGC 4382	0.25	0.11	0.02	0.09	1.15	0.25	3.69	0.54	2.29	0.32	5.98	0.85
NGC 4387	0.29	0.11	0.26	0.09	0.51	0.25	2.85	0.29	2.27	0.22	5.12	0.41
NGC 4406	0.06	0.11	0.15	0.09	0.38	0.25	2.37	0.29	2.37	0.18	4.74	0.41
NGC 4435	0.39	0.11	0.24	0.09	0.26	0.25	2.87	0.47	2.09	0.18	4.96	0.41
NGC 4442	0.17	0.11	0.54	0.12	0.19	0.48	2.28	0.77	1.60	0.23	3.88	0.85
NGC 4468	0.71	0.11	0.29	0.09	1.05	0.25	3.03	0.29	2.22	0.18	5.25	0.41
NGC 4472	0.27	0.11	0.30	0.09	0.29	0.25	2.52	0.29	2.32	0.18	4.84	0.41
NGC 4478	0.32	0.29	0.32	0.09	0.60	0.25	2.63	0.29	1.90	0.18	4.54	0.41
NGC 4486	0.73	0.11	0.36	0.09	0.42	0.25	2.50	0.29	1.90	0.18	4.39	0.41
NGC 4552	0.48	0.11	0.20	0.09	0.25	0.25	2.52	0.29	2.01	0.18	4.53	0.41
NGC 4636	0.42	0.11	0.14	0.09	0.49	0.25	2.62	0.29	2.35	0.18	4.97	0.41
NGC 4660	0.13	0.11	0.20	0.09	0.53	0.36	2.76	0.29	3.02	0.18	5.78	0.41
NGC 4754	0.39	0.11	0.26	0.09	0.58	0.25	3.05	0.29	1.77	0.18	4.83	0.41
Coma Galaxies												
NGC 4874	0.20	0.14	-0.27	0.21	0.16	0.71	2.21	0.57	2.12	0.31	4.33	0.77
NGC 4881	0.51	0.18	0.30	0.15	0.61	0.38	2.75	0.39	1.68	0.47	4.43	0.74
NGC 4886	0.33	0.17	-0.27	0.23	1.34	0.46	2.95	0.43	1.80	0.36	4.75	0.70
NGC 4889	0.98	0.18	0.05	0.12	1.28	0.25	3.19	0.29	2.15	0.18	5.34	0.41
NGC 4906	0.34	0.15	-0.03	0.24	0.73	0.28	2.49	0.29	2.05	0.32	4.54	0.41
NGC 4923	-0.11	0.20	0.17	0.11	0.70	0.25	2.84	0.29	1.79	0.29	4.63	0.41
IC 3998	0.02	0.22	0.01	0.23	1.84	0.96	2.81	0.71	3.27	0.38	6.08	0.72
IC 4011	0.57	0.14	-0.30	0.29	1.04	0.56	3.09	0.69	2.31	0.76	5.40	1.15
IC 4012	0.41	0.32	0.03	0.36	-0.18	0.62	2.45	0.90	1.45	0.79	3.91	1.27
IC 4026	0.67	0.21	0.39	0.19	0.50	0.40	3.89	0.76	2.53	0.59	6.42	0.89
Field Galaxies												
NGC 2723	0.51	0.11	-0.05	0.10	0.31	0.36	2.64	0.29	1.95	0.25	4.59	0.51
NGC 2872	-0.12	0.11	0.19	0.09	-0.48	0.25	1.76	0.29	0.87	0.18	2.63	0.41
NGC 2974	0.66	0.11	0.12	0.09	0.71	0.25	2.95	0.29	1.53	0.18	4.48	0.41
NGC 3115	0.40	0.11	0.29	0.09	0.77	0.25	2.83	0.29	2.00	0.18	4.83	0.41
NGC 3156	-0.13	0.11	0.26	0.13	0.68	0.25	2.44	0.29	1.77	0.18	4.21	0.41
NGC 3379	0.44	0.11	0.21	0.09	0.14	0.25	2.29	0.29	1.77	0.18	4.06	0.41
NGC 3384	0.11	0.11	0.36	0.09	0.80	0.25	3.05	0.29	2.31	0.18	5.36	0.41

^aall indices are defined in Table 2 and are measured as pseudo-equivalent widths in Å

Table 4: The Molecular Band Index Measurements^a

Galaxy	I7100	σ	I7450	σ	I7890	σ	S7890	σ	I8197	σ	I8460	σ
Virgo Galaxies												
NGC 4124	0.056	0.003	-0.003	0.007	0.059	0.011	0.047	0.013	0.015	0.009	0.040	0.012
NGC 4179	0.096	0.005	-0.009	0.004	0.078	0.005	0.061	0.006	0.039	0.005	0.057	0.008
NGC 4374	0.093	0.003	0.005	0.004	0.067	0.005	0.047	0.006	0.027	0.005	0.063	0.006
NGC 4377	0.078	0.003	0.001	0.011	0.077	0.005	0.052	0.006	0.023	0.005	0.054	0.006
NGC 4382	0.069	0.003	-0.004	0.004	0.059	0.010	0.027	0.012	0.019	0.005	0.041	0.010
NGC 4387	0.075	0.004	-0.011	0.004	0.069	0.005	0.046	0.006	0.015	0.005	0.051	0.009
NGC 4406	0.087	0.003	-0.014	0.004	0.090	0.005	0.068	0.006	0.030	0.005	0.038	0.006
NGC 4435	0.081	0.003	-0.008	0.004	0.074	0.005	0.059	0.006	0.023	0.005	0.063	0.006
NGC 4442	0.103	0.003	-0.006	0.006	0.084	0.005	0.061	0.006	0.035	0.008	0.050	0.006
NGC 4468	0.075	0.005	-0.023	0.004	0.066	0.011	0.038	0.014	0.025	0.009	0.042	0.006
NGC 4472	0.103	0.003	-0.002	0.004	0.085	0.005	0.059	0.006	0.044	0.005	0.056	0.006
NGC 4478	0.080	0.003	-0.003	0.004	0.073	0.005	0.044	0.006	0.029	0.005	0.059	0.006
NGC 4486	0.102	0.003	-0.008	0.004	0.090	0.005	0.063	0.006	0.031	0.008	0.064	0.006
NGC 4552	0.105	0.003	0.001	0.004	0.087	0.005	0.066	0.006	0.051	0.005	0.052	0.006
NGC 4636	0.095	0.004	-0.007	0.004	0.077	0.005	0.054	0.006	0.032	0.005	0.049	0.006
NGC 4660	0.079	0.003	0.000	0.004	0.084	0.005	0.063	0.006	0.027	0.005	0.063	0.006
NGC 4754	0.090	0.003	-0.007	0.004	0.084	0.005	0.057	0.006	0.030	0.005	0.048	0.006
Coma Galaxies												
NGC 4874	0.107	0.005	0.006	0.007	0.060	0.007	0.019	0.008	0.030	0.005	0.041	0.010
NGC 4881	0.086	0.006	-0.015	0.004	0.080	0.008	0.047	0.012	0.027	0.007	0.066	0.014
NGC 4886	0.086	0.005	0.006	0.012	0.075	0.006	0.051	0.006	0.041	0.007	0.054	0.011
NGC 4889	0.112	0.007	0.000	0.014	0.096	0.006	0.072	0.006	0.039	0.007	0.065	0.006
NGC 4906	0.091	0.005	0.002	0.007	0.082	0.007	0.061	0.011	0.035	0.008	0.044	0.019
NGC 4923	0.089	0.004	-0.001	0.006	0.087	0.005	0.058	0.006	0.020	0.007	0.046	0.006
IC 3998	0.112	0.009	0.000	0.007	0.070	0.014	0.029	0.018	0.019	0.009	0.013	0.013
IC 4011	0.090	0.010	-0.014	0.013	0.064	0.009	0.031	0.011	0.038	0.015	0.035	0.023
IC 4012	0.082	0.020	0.011	0.011	0.061	0.012	0.022	0.022	0.029	0.011	0.065	0.029
IC 4026	0.073	0.006	-0.013	0.012	0.093	0.008	0.062	0.009	0.052	0.008	0.033	0.015
Field Galaxies												
NGC 2723	0.081	0.003	-0.017	0.004	0.072	0.006	0.058	0.008	0.040	0.005	0.035	0.007
NGC 2872	0.087	0.003	-0.012	0.004	0.076	0.005	0.054	0.006	0.029	0.005	0.043	0.006
NGC 2974	0.086	0.003	0.023	0.004	0.092	0.005	0.063	0.006	0.044	0.005	0.069	0.006
NGC 3115	0.089	0.003	0.005	0.004	0.075	0.005	0.052	0.006	0.030	0.005	0.051	0.006
NGC 3156	0.034	0.003	0.003	0.004	0.060	0.007	0.025	0.010	0.009	0.005	0.049	0.007
NGC 3379	0.080	0.003	-0.005	0.004	0.066	0.005	0.043	0.006	0.037	0.005	0.052	0.006
NGC 3384	0.084	0.003	-0.001	0.004	0.080	0.005	0.056	0.006	0.028	0.005	0.043	0.006

^aall indices are defined in Table 2 and are measured as absorption in mag.

Table 5: The CO Index Measurements^a

Galaxy	z	CO_{obs}^b	σ	CO^c	σ	$\Delta(\text{CO})^d$	σ
Virgo Galaxies							
NGC 4124	0.00544	0.114	0.029	0.104	0.022	-0.010	0.036
NGC 4179	0.00419	0.184	0.010	0.204	0.009	0.020	0.013
NGC 4374	0.00343	0.170	0.010	0.185	0.009	0.015	0.013
NGC 4377	0.00453	0.163	0.010	0.183	0.009	0.020	0.013
NGC 4382	0.00241	0.193	0.010	0.206	0.009	0.013	0.013
NGC 4387	0.00187	0.147	0.010	0.157	0.009	0.010	0.013
NGC 4406	-0.00083	0.188	0.013	0.185	0.013	-0.003	0.018
NGC 4435	0.00261	0.174	0.010	0.179	0.012	0.005	0.016
NGC 4442	0.00177	0.210	0.010	0.206	0.009	-0.003	0.013
NGC 4468	0.00299	0.184	0.023	0.168	0.016	-0.016	0.028
NGC 4472	0.00328	0.189	0.010	0.205	0.009	0.015	0.013
NGC 4478	0.00461	0.150	0.010	0.173	0.009	0.023	0.013
NGC 4486	0.00428	0.182	0.010	0.211	0.010	0.029	0.014
NGC 4552	0.00104	0.194	0.010	0.198	0.009	0.004	0.013
NGC 4636	0.00309	0.182	0.010	0.197	0.009	0.015	0.013
NGC 4660	0.00365	0.173	0.010	0.190	0.009	0.017	0.013
NGC 4754	0.00466	0.194	0.010	0.217	0.009	0.023	0.013
Coma Galaxies							
NGC 4874	0.02386	0.031	0.010	0.118	0.016	0.087	0.019
NGC 4881	0.02237	0.058	0.036	0.162	0.051	0.104	0.062
NGC 4886	0.02117	0.007	0.046	0.050	0.071	0.043	0.085
NGC 4889	0.02166	0.072	0.010	0.216	0.009	0.145	0.013
NGC 4906	0.02492	0.065	0.010	0.171	0.023	0.107	0.025
NGC 4923	0.01820	0.080	0.010	0.162	0.018	0.083	0.021
IC 3998	0.03132	-0.021	0.035	0.219	0.097	0.240	0.103
IC 4011	0.02405	0.004	0.032	0.288	0.119	0.284	0.123
IC 4012	0.02409	0.046	0.068	0.136	0.053	0.090	0.086
IC 4026	0.02714	-0.045	0.029	0.134	0.063	0.179	0.069
Field Galaxies							
NGC 2723	0.01243	0.136	0.010	0.180	0.009	0.044	0.013
NGC 2872	0.01005	0.141	0.022	0.178	0.021	0.037	0.030
NGC 2974	0.00669	...	...	...	...	...	...
NGC 3115	0.00224	0.181	0.010	0.190	0.009	0.009	0.013
NGC 3156	0.00373	0.143	0.019	0.155	0.015	0.012	0.024
NGC 3379	0.00297	0.142	0.010	0.160	0.009	0.018	0.013
NGC 3384	0.00245	0.182	0.010	0.195	0.009	0.013	0.013

^athe CO index is defined in Table 2 and is measured as absorption in mag.^bthe CO index measured from the *observed* spectra^cthe CO index measured from the redshift-corrected spectra^dCO - CO_{obs}

Table 6: Linear Least-Squares Fits to the Virgo Spectral Indices^a

x	y	Intercept	σ	Slope	σ	r^b	p^c
$K_{-0.3}$	$(V - K)_0$	3.854	0.101	-0.086	0.013	-0.883	99.9
$K_{-0.3}$	$(J - K)_0$	1.058	0.044	-0.024	0.006	-0.785	99.9
$K_{-0.3}$	$(H - K)_0$	0.248	0.025	-0.004	0.003	-0.455	91.0
$K_{-0.3}$	CO	0.270	0.025	-0.010	0.003	-0.728	99.8
$K_{-0.3}$	I(7100)	0.155	0.014	-0.009	0.002	-0.804	99.9
$K_{-0.3}$	I(7450)	0.015	0.009	-0.003	0.001	-0.627	98.8
$K_{-0.3}$	I(7890)	0.110	0.011	-0.004	0.001	-0.679	99.5
$K_{-0.3}$	S(7890)	0.086	0.011	-0.004	0.001	-0.662	99.4
$K_{-0.3}$	I(8197)	0.069	0.012	-0.005	0.002	-0.697	99.7
$K_{-0.3}$	I(8460)	0.066	0.011	-0.002	0.001	-0.460	91.4
$K_{-0.3}$	Na I	1.210	0.206	-0.106	0.026	-0.766	99.9
$K_{-0.3}$	Mg8807	0.223	0.137	0.009	0.018	0.422	88.2
$K_{-0.3}$	Ca8498	1.198	0.315	-0.102	0.042	-0.623	98.8
$K_{-0.3}$	Ca8542	2.916	0.322	-0.030	0.043	-0.408	86.8
$K_{-0.3}$	Ca8662	1.481	0.544	0.079	0.071	0.450	90.6
$K_{-0.3}$	Ca II	4.133	0.726	0.089	0.096	0.429	88.8
$(V - K)_0$	$(J - K)_0$	0.059	0.174	0.254	0.054	0.804	99.9
$(V - K)_0$	$(H - K)_0$	-0.023	0.090	0.075	0.028	0.644	99.1
$(V - K)_0$	CO	-0.276	0.091	0.145	0.028	0.844	99.9
$(V - K)_0$	I(7100)	-0.241	0.036	0.103	0.011	0.932	99.9
$(V - K)_0$	I(7450)	-0.093	0.042	0.027	0.013	0.577	97.6
$(V - K)_0$	I(7890)	-0.069	0.051	0.046	0.016	0.692	99.6
$(V - K)_0$	S(7890)	-0.098	0.050	0.048	0.016	0.699	99.7
$(V - K)_0$	I(8197)	-0.182	0.046	0.066	0.014	0.804	99.9
$(V - K)_0$	I(8460)	-0.018	0.051	0.022	0.016	0.485	93.2
$(V - K)_0$	Na I	-3.577	0.839	1.239	0.262	0.808	99.9
$(V - K)_0$	Mg8807	0.318	0.643	-0.009	0.200	-0.407	86.7
$(V - K)_0$	Ca8498	-1.896	1.402	0.728	0.437	0.527	95.5
$(V - K)_0$	Ca8542	2.005	1.498	0.214	0.465	0.389	84.8
$(V - K)_0$	Ca8662	5.671	2.437	-1.116	0.758	-0.495	93.8
$(V - K)_0$	Ca II	9.512	3.130	-1.463	0.972	-0.500	94.1
$(J - K)_0$	$(H - K)_0$	-0.028	0.064	0.283	0.073	0.751	99.8
$(J - K)_0$	CO	-0.039	0.086	0.263	0.098	0.682	99.6
$(J - K)_0$	I(7100)	-0.150	0.036	0.274	0.041	0.885	99.9
$(J - K)_0$	I(7450)	-0.051	0.037	0.051	0.042	0.465	91.8
$(J - K)_0$	I(7890)	0.012	0.039	0.078	0.044	0.565	97.2
$(J - K)_0$	S(7890)	-0.020	0.038	0.088	0.043	0.587	97.9
$(J - K)_0$	I(8197)	-0.118	0.034	0.171	0.039	0.789	99.9
$(J - K)_0$	I(8460)	0.002	0.042	0.058	0.048	0.463	91.6
$(J - K)_0$	Na I	-3.007	0.682	3.903	0.784	0.821	99.9
$(J - K)_0$	Mg8807	-0.095	0.456	0.439	0.522	0.451	90.7
$(J - K)_0$	Ca8498	-0.326	1.118	0.874	1.279	0.413	87.3
$(J - K)_0$	Ca8542	3.952	0.956	-1.442	1.093	-0.478	92.7
$(J - K)_0$	Ca8662	5.816	1.668	-4.267	1.905	-0.593	98.0
$(J - K)_0$	Ca II	10.062	1.910	-6.018	2.183	-0.653	99.3

^aNGC 4382 and NGC 4435 omitted from fitting^blinear least-squares correlation coefficient^cpercent probability that x, y distribution is not random

Figure 4: Bandpasses used to measure the red atomic and molecular indices. All indices are defined in Table 2. Feature bandpasses are shown below the spectrum of NGC 3115; continuum bandpasses are shown above the spectrum.

Figure 5: The difference in the CO band strength measured from the *observed* and redshift-corrected near-infrared spectra is plotted as a function of the redshift of the galaxies observed. Elliptical galaxies in the Virgo and Coma clusters are shown as filled and open circles, respectively. Virgo S0 galaxies are represented by open triangles; Coma S0 galaxies are open squares. For field galaxies, ellipticals are shown as asterisks, while lenticulars are shown as crosses. The solid line is a linear least-squares fit to the data and has a slope of +5.23.

Figure 6: The color-magnitude diagrams for the early-type galaxy nuclei. The Virgo galaxies are shown in the left-hand panels; the Virgo E and S0 galaxies are represented by filled dots and triangles, respectively. The Coma and field galaxies are shown in the right-hand panels. Coma E and S0 galaxies are represented by open dots and open squares, respectively; the field E and S0 galaxies are shown as asterisks and crosses, respectively. The heavy solid lines represent linear least-squares fits to the filled Virgo points; the open triangles are the galaxies NGC 4382 and NGC 4435 and have been omitted from the fits (see text). The dotted lines represent the 99% confidence limits for the linear fits.

Figure 7: The $(V - K)_0$, $(J - K)_0$ diagrams for the nuclei of early-type galaxies. All symbols and lines have the same meaning as in Figure 6.

Figure 8: The $(H - K)_0$ color diagrams for the nuclei of early-type galaxies. All symbols and lines have the same meaning as in Figure 6.

Figure 9: The behavior of the CO index with luminosity and color in the nuclei of early-type galaxies. All symbols and lines have the same meaning as in Figure 6.

Figure 10: The behavior of the H_2O index with luminosity and color in the nuclei of early-type galaxies. All symbols and lines have the same meaning as in Figure 6.

Figure 11: The behavior of the $I(7100)$ index with luminosity and color in the nuclei of early-type galaxies. All symbols and lines have the same meaning as in Figure 6.

Figure 12: The behavior of the $I(7450)$ index with luminosity and color in the nuclei of early-type galaxies. All symbols and lines have the same meaning as in Figure 6.

Figure 13: The behavior of the $I(7890)$ index with luminosity and color in the nuclei of early-type galaxies. All symbols and lines have the same meaning as in Figure 6.

Figure 14: The behavior of the $S(7890)$ index with luminosity and color in the nuclei of early-type galaxies. All symbols and lines have the same meaning as in Figure 6.

Figure 15: The behavior of the $I(8197)$ index with luminosity and color in the nuclei of early-type galaxies. All symbols and lines have the same meaning as in Figure 6.

Figure 16: The behavior of the $I(8460)$ index with luminosity and color in the nuclei of early-type galaxies. All symbols and lines have the same meaning as in Figure 6.

Figure 17: The behavior of the Na I index with luminosity and color in the nuclei of early-type galaxies. All symbols and lines have the same meaning as in Figure 6.

Figure 18: The behavior of the Mg8807 index with luminosity and color in the nuclei of early-type galaxies. All symbols and lines have the same meaning as in Figure 6.

Figure 19: The behavior of the Ca8498 index with luminosity and color in the nuclei of early-type galaxies. All symbols and lines have the same meaning as in Figure 6.

Figure 20: The behavior of the Ca8542 index with luminosity and color in the nuclei of early-type galaxies. All symbols and lines have the same meaning as in Figure 6.

Figure 21: The behavior of the Ca8662 index with luminosity and color in the nuclei of early-type galaxies. All symbols and lines have the same meaning as in Figure 6.

Figure 22: The behavior of the Ca II index with luminosity and color in the nuclei of early-type galaxies. All symbols and lines have the same meaning as in Figure 6.

CHAPTER IV

MODELS OF THE GALACTIC BULGE

Whitford (1978) first demonstrated quantitatively that the Galactic bulge, other spiral bulges and early-type galaxies have very similar integrated spectra. More recent work has generally confirmed that the stars in the Galactic bulge are probably the closest Milky Way counterparts to the stellar populations that make up early-type systems (see *e.g.* Frogel 1988). This is the basic assumption which underlies the use of bulge stars to model the light of early-type galaxies. Assuming that the Galactic bulge and elliptical galaxies have had similar star formation histories, the properties of the bulge population as a function of galactocentric radius should be indicative of the radial population gradients observed in elliptical galaxies.

The evidence for population gradients in elliptical and S0 galaxies was summarized in Chapter 1. Do spiral bulges, including that of the Milky Way, show radial gradients similar to those seen in early-type galaxies? Current evidence seems to indicate that this is the case. Balcells & Peletier (1994) have found that bulges of spirals show color gradients similar to those seen in early-type galaxies; when only the bulge luminosity is considered, spiral bulges also appear to follow the same color-magnitude relation that E/S0 galaxies exhibit. Thus, since the Galactic bulge appears to be typical of spiral bulges in general, its integrated spectral and photometric properties as a function of

latitude should be a good representation of the integrated light of early-type galaxies as a function of radius.

This chapter describes the construction of a series of Galactic bulge models. First, a general description of the modelling process is given. Then, the observational data used in the models is presented. The integrated model of Baade's Window (BW) is next described and examined in some detail; the resulting colors and spectral indices are compared to the nuclear measurements of the Virgo early-type galaxies from Chapter 3. Finally, models of Galactic bulge fields at $b = -6^\circ$ and $b = -8^\circ$ are described. The derivation of the radial gradients in the Galactic bulge is postponed until Chapter 5.

4.1 General Description of the Models

For comparison with the early-type galaxy data, the basic goal of the modelling is to simulate the integrated *VIJHK*, CO and H₂O photometry and the spectral indices defined in Table 2. Since it is not possible to collect this complete set of data for every star in each Galactic bulge field to be modelled, some of this information must necessarily be derived from other observational data or from theoretical considerations. For these reasons, it was the available observational data which dictated the specific methodology used to build the Galactic bulge models.

The Galactic bulge fields to be modelled (BW and fields along the minor axis of the bulge at $b = -6^\circ$ and $b = -8^\circ$) were chosen specifically because the stellar populations there have been extensively observed. The information available for the stellar populations of each of these fields included:

- Cousins VI color-magnitude diagrams (CMDs) from Terndrup (1988; hereafter T88), which give color and magnitude information for the global stellar population brighter than some limiting magnitude,
- infrared photometry from Frogel & Whitford (1982, 1987; hereafter FW82 and FW87, respectively) and Frogel *et al.* (1990; hereafter FTBW) of a representative sample of the late-type giants, and
- red spectroscopy from Terndrup *et al.* (1990; hereafter TFW) of an unbiased subsample of the late-type giants observed in the infrared.

Thus, to simulate the integrated colors and spectral indices of any particular Galactic bulge field, the following basic approach was taken:

1. specify the general distribution of the stellar population in the Cousins I_0 , $(V - I)_0$ color-magnitude diagram,
2. transform the $(V - I)_0$ colors to $(H - K)_0$ colors,
3. predict all of the other photometric and spectroscopic indices from the $(H - K)_0$ colors, and
4. sum the data from the CMD to produce the integrated colors and spectral indices of the entire stellar population.

It should be emphasized that such a model does not synthesize an integrated spectrum of the Galactic bulge; it predicts the strengths of the integrated colors and spectral features of the stellar population.

Overall, this means that the models require only three basic pieces of information: (1) a Cousins VI CMD, (2) an I -band luminosity function (LF), and (3) calibration relations which allow the colors and spectral indices of individual stars to be predicted from the CMD and the LF. In this scheme, the CMD and LF work together to specify the color and luminosity distribution of the *entire* stellar population. Since any photometry is necessarily limited in magnitude, this requires a theoretical extension of the CMD to faint magnitudes. With respect to the LF, the Cousins I band was chosen because this band is centered very near the central wavelength of the red spectra. Computing the integrated spectral indices requires a knowledge of the brightness of each star at the wavelength of the spectral feature measured, and the I -band magnitudes are good approximations to these luminosities for most of the spectral indices.

In constructing these models, three possibilities have been allowed for specifying the distribution of bulge stars in the $I_0, (V - I)_0$ plane - photometry of individual stars (a CMD), a sequence giving the average color of the stars as a function of magnitude (a ridge line), or a combination in which the brighter part of the stellar population is represented by a CMD, while the fainter part is represented by a ridge line. When a CMD is used, stars lying in specified regions of the color-magnitude plane can be excluded from the model, the I -band LF is extracted directly from the observational data, and the LF can be binned as desired. For a ridge line, the LF must be specified and a pseudo-CMD is built by providing the following information for the stars in each LF bin: the average I_0 magnitude, the average $(V - I)_0$ color, the number of

stars and the width of the color distribution. In each I_0 bin, the stars are then laid out in a Gaussian color distribution of the specified width and mean color. Additionally, for any of these three options, the $(V - I)_0$ bin size must be chosen.

Once the I_0 , $(V - I)_0$ distribution of stars has been determined, the star counts are binned in color and magnitude. Because the aforementioned calibration relations differ for giants and dwarfs, the stellar distribution must then be divided into three zones, representing the color-magnitude domains of the giants, subgiants and dwarfs. This is accomplished by specifying the I_0 and $(V - I)_0$ limits of a rectangular region which encloses the subgiants. All of the stars in any color, magnitude bin which overlaps this subgiant region are considered to be subgiants. At all colors, stars brighter than the bright edge of the subgiant box are assumed to be giants, and those fainter than its faint boundary are labelled dwarfs. Over the magnitude range of the subgiants, the stars bluer than the subgiants are considered to be dwarfs and those redder than the subgiants are called giants.

Once the giants, dwarfs and subgiants have been discriminated, separate calibration relations are used to derive the photometric and spectroscopic parameters for each of these subpopulations of stars. As mentioned above, the need for these calibration relations is dictated by the fact that a full set of the necessary photometry ($VIJHK$, CO and H_2O) and red spectroscopy is not available for a complete sample of the stellar population in each of the Galactic bulge fields modelled. The VI CMDs (T88) sample the giant stars of a given bulge field fairly completely. However, the infrared photometry and red spectra (FW82, FW87, FTBW and TFW) represent

different samples of giants at the same Galactic latitude. Observations of a significant number of known Galactic bulge dwarfs and subgiants do not exist. Thus, the purpose of the calibration relations is to bridge the gap between the group of stars in the CMD and those observed in the bulge late-type giant surveys and to provide a means to assign photometric and spectroscopic characteristics to the subgiants and dwarfs. $(H - K)_0$ colors were specifically chosen as a basis for the calibration relations because the color, spectral index relationships showed the least scatter when $(H - K)_0$ was the color used. Because stellar population gradients could cause the calibration relations to differ between the Galactic bulge fields modelled, the derivation of these relations is described later in this chapter.

After the calibration relations have been used to find the colors, molecular band indices and atomic line pseudo-equivalent widths for all of the stars in the CMD, a luminosity-weighted sum of each parameter produces the integrated colors and spectral feature strengths. In determining this integrated data, the near-infrared CO and H₂O indices are weighted by the K magnitudes, and the red spectral feature strengths are weighted by the I magnitudes. The integrated atomic line pseudo-equivalent widths, $W(\text{line})$, and molecular band indices, $I(\text{band})$, are then given by

$$W(\text{line}) = \frac{\sum N_i W_i 10^{-0.4m_i}}{\sum N_i 10^{-0.4m_i}} \quad (4)$$

and

$$I(\text{band}) = -2.5 \log \left[\frac{\sum N_i 10^{-0.4(m_i + I_i)}}{\sum N_i 10^{-0.4m_i}} \right], \quad (5)$$

respectively, where N_i is the number of stars in a given color-luminosity bin, W_i and I_i are the line and band strength, respectively, predicted by the appropriate calibration

relation for a star of that color, and m_i is the apparent magnitude of the LF bin used in the weighting.

Overall, the course of the modelling was influenced by the observational data in possession. Unfortunately, the actual photometry presented in the CMDs of T88 was not available for use in the Galactic bulge models. However, Terndrup (1994, private communication) kindly provided individual stellar photometry for a field in Baade's Window at $b = -3.9^\circ$. For this reason, the BW model was constructed first, and the dependence of the model results upon the various input parameters was examined. The information which was used for the BW model was then suitably adjusted, based upon observations of stars in the Galactic bulge at other latitudes, to simulate the integrated spectrum of the bulge at these latitudes.

Since the models require calibration relations which predict the colors and spectral feature strengths of individual stars from their $(V - I)_0$ colors, such relations have been constructed from observations of individual bulge stars. In the next section, a simple description is given of the photometry selected from the literature and the measurement of the spectral indices used to derive these calibration relations.

4.2 The Galactic Bulge M Giant Surveys

Because the BW stellar population contains an unexpectedly high proportion of M giants, Blanco *et al.* (1984; hereafter BMB) and Blanco & Blanco (1986) were prompted to perform grism surveys of this region in order to identify and classify these stars. Due to the nature of the grism work, the completeness of their sample was limited to spectral types M2 and cooler, so these stars will be referred to here as the M2+

giants.

Infrared photometry of an unbiased sample of the M2+ giants in BW was obtained by FW87 and used to extensively study this population. FTBW extended the grism surveys to other fields along the minor axis of the Galactic bulge, identified similar late-type stars there and obtained infrared photometry for many of these M2+ giants as well. TFW and Terndrup *et al.* (1991) then used red and infrared spectroscopy, respectively, to examine the characteristics of the M2+ giants in each of these fields. This body of work provided much of the data used to model the integrated light of the Galactic bulge.

4.2.1 Photometry

Most of the photometry of the bulge M2+ giants used to derive the calibration relations was taken from FW82 and FW87 for the Baade's Window stars and from FTBW for stars in the -6° and -8° bulge fields; however, the H_2O values were often rounded off or truncated in FTBW, so the more precise TFW values were used instead. For stars observed more than once, the photometry used in the calibration relations was the set of data for which a bolometric magnitude had been given by FW87 or FTBW; this was usually also the observation incorporating the most colors.

All of this photometry was corrected for extinction and reddening using the following prescription: (1) reddening values taken from the literature were assumed to be appropriate for an A0 star and were designated $E_0(B - V)$; (2) since the model calibration relations are based mainly upon observations of M giants, an intrinsic $(B - V)_0$ color of 1.20 mag. was assumed, which gives $E(B - V) = 0.904 E_0(B - V)$

per Dean *et al.* (1978); (3) the reddening ratios for M supergiants from Elias *et al.* (1985) were used to estimate the other extinction and reddening values whenever possible; (4) the M star reddening law of Cohen *et al.* (1981) was used to derive the extinction in the Cousins *I* band; and (5) $E(V - I) = A_V - A_I$ was used.

The resulting extinction and reddening corrections are given in Table 7; this table also gives values for the Sgr I field at $b \sim -3^\circ$ because photometry of giants in this bulge field were used to help define the calibration relations for BW (see Section 4.3.3). Note that the $E_0(B - V)$ value used for BW is different than that used by FW82 and FW87; this is not true for any of the other Galactic bulge fields. However, the method used to derive the reddening ratios here is slightly different than that used by FTBW, so some of the other corrections differ slightly from their values. All of the reddening-corrected photometry reported by FW82, FW87 and FTBW has been adjusted using the Table 7 corrections before being used in the definition of the calibration relations.

4.2.2 Spectroscopy

To facilitate the modelling of the integrated spectral feature strengths of the Galactic bulge, Don Terndrup kindly made available the fully-reduced Galactic bulge and field star spectra presented by TFW. This collection consists of spectra centered near 8400 Å for stars in six fields along the minor axis of the Galactic bulge; the stellar sample is made up primarily of Galactic bulge M2+ giants, but it includes some bulge K-M1 giants, field giants and nearby field dwarfs. Although TFW measured the molecular band indices in Table 2 for all of these spectra, they did not measure atomic

line strengths. For consistency, all of the Table 2 spectral indices were measured here in the same manner described in Chapter 3 for the early-type galaxy spectra.

Before measuring the spectral indices, these spectra were corrected for telluric absorption, applying the same correction algorithm used for the early-type galaxy spectra (see Chapter 2); such corrections had not been made by TFW because the spectral regions they used to measure most of the TiO band strengths were specifically chosen to avoid telluric features. However, the I(8197) index falls directly within the z band of telluric H₂O (see Figure 3), so it is unavoidably contaminated in uncorrected data. In addition, the Na I doublet at $\lambda\lambda 8183, 8195$ Å and possibly the Mg I $\lambda 8807$ Å line, neither of which were studied by TFW, are affected by telluric H₂O absorption.

As discussed by TFW, the bulge spectra were obtained at two different spectral resolutions, which will be designated here as high-resolution (2.33 Å pixel⁻¹) and low-resolution (5.75 Å pixel⁻¹). When both high- and low-resolution spectra were available for a given star, only the low-resolution spectra were considered; this was done for the following reasons: (1) wavelength and flux calibration uncertainties at the edges of the high-resolution spectra cause some of the spectral index measurements to be less certain for these spectra, and (2) averaging the high- and low-resolution spectral indices would be inappropriate for variable stars. Since the spectra sample different wavelength regimes, some features can be measured only in the low-resolution spectra, while others can be measured from both the high- and low-resolution data. The average strengths of features present in both types of spectra would not represent the same average “epoch” as those found in only the low-resolution spectra.

All of the stars identified as M2+ giants in the grism surveys were initially assigned to the spectral bins M2-4, M5-6 or M7+ by FW87, FTBW or TFW (the M6.5 BW stars listed in FW87 were assigned to the M5-6 bin). However, as described in TFW, these initial spectral determinations were based upon the classification scheme of Nassau & Velghe (1964), which produces spectral types which are not on the MK system. Many of these stars were later determined to be either: (1) stars having spectral types earlier than M2, or (2) field dwarfs along the line of sight to the Galactic bulge. FTBW detected many such misclassifications by comparing the photometry of the grism stars to field star relations; they then designated all of the apparent dwarfs and pre-M2 giants as foreground stars.

To assign these stars less subjective and more consistent spectral types, the S(7890) and I(8460) indices of the field stars observed by TFW were plotted against their MK types. Figure 23 shows these plots and includes a quadratic fit to the data for field stars with spectral types later than M0. These relations were used to determine what will be called the MK type of each Galactic bulge star and to assign it to the appropriate MK spectral bin. Using these new spectral bins, the sample of stars in each bulge field was then split into the M2+ and the K-M1 stars. Unlike FTBW, the pre-M2 stars which appeared to be normal giants were assumed to be members of the Galactic bulge.

In addition, the strength of the Na I doublet could be used to detect field dwarfs. Since Wolf 359, a known M6 field dwarf, has a measured Na I strength of 5.68 Å (see Table 29), any bulge star with $W(\text{Na I}) > 1.0 \text{ Å}$ was examined more closely to

determine if it could be a nearby M dwarf. As done by TFW, the *observed* colors of such stars (and stars not observed spectroscopically) were also compared to the field dwarf sequences in the $(J - H)_0$ vs. $(H - K)_0$ and CO vs. $(J - K)_0$ diagrams. These tests allowed field dwarfs to be removed from the bulge star sample. To better define the field dwarf calibration relations, the surveys of the -10° and -12° Galactic bulge fields, which were not modelled but which were observed by FTBW and TFW, were also searched for foreground dwarfs.

The measurements of the spectral indices for the Galactic bulge and field stars are presented in Tables 8 - 29. These tables are arranged in pairs, molecular band indices and atomic line indices, for each of the following groups of stars (in the order given): the Sgr I M2+ giants, the Sgr I K-M1 giants, the BW M2+ giants, the BW K-M1 giants, the -6° M2+ giants, the -6° K-M1 giants, the -8° M2+ giants, the -8° K-M1 giants, the field M2+ giants, the field K-M1 giants, and the field dwarfs. The first column of each table is the star number taken from either FW82, FW87, FTBW or TFW. Columns 2 and 3 of the tables containing the molecular band indices give the spectral type bins of the stars. The Blanco bins are those given by FW87 or FTBW and were derived from the spectral types originally assigned by either BMB or Blanco & Blanco (1986) for the BW stars. The MK bins were derived from the TiO bands as described above; all pre-M2 stars have been assigned to MK spectral bin 0. Due to the aforementioned contamination by telluric absorption, the I(8197) strengths reported here should supercede those given in TFW. However, except in a very few cases, the other molecular band indices measured here are indistinguishable

from theirs.

4.2.3 Comments on the Bulge M Giant Data

In a few cases, discrepancies were found in the photometry, spectroscopy or spectral types reported by different sources for the bulge stars observed in the grism surveys. For the sake of completeness, the following sections describe such discrepancies, when they affected the selection of information from the literature. This section also discusses the foreground stars found by FTBW, including the detection of field dwarfs, and mentions stars having otherwise interesting spectra.

The Sgr I (-3°) Field

FTBW listed eight stars in the Sgr I sample as foreground stars. Of these, stars 3-040, 3-074 and 3-106 have the colors and CO strengths of pre-M2 dwarfs. Stars 3-007, 3-055, 3-093 and 3-137 have also been verified to have spectral types earlier than M2, but since they are very blue, it can not be determined whether they are giants or dwarfs; they have been assumed to be giants. Star 3-103, the eighth field star from FTBW, appears to have the spectrum of a normal M2-4 giant, but it does have unusual colors for its TiO band strengths; this star could be a double or a variable, or its photometry could be in error. Since the -3° field is very crowded, the spectrum and photometry may not actually represent the same star.

Stars 3-035 and 3-039 are probably variables; spectra taken at different epochs show differences in TiO band strengths which are greater than those usually seen in non-variable stars. In addition, star 3-068 could be a binary; its spectrum appears

to be that of a normal M giant, except the continuum shows a blue excess - the continuum initially falls from 6000 to ~ 6800 Å and then rises again to the red.

Stars 3-007, 3-093, 3-137 and 3-147 have very interesting spectra; they could be supergiants lying on the far side of the bulge. The spectra of these stars show a strong Ca II triplet, strong CN bands in the 7900 - 8400 Å region and a variety of atomic lines which are indicative of supergiants - *e.g.* metallic blends at 6362 Å and 6497 Å, Fe I λ 6945, Fe I λ 6979 and Fe I ,Co I λ 7016 (Turnshek *et al.*, 1985; Kirkpatrick, Henry & McCarthy, 1991; Torres-Dodgen & Weaver, 1993). Quantitatively, however, the measured Ca II indices of these stars are not actually any stronger than those of the other K-M1 stars in this field. Instead, many of these other spectral features may be sensitive to metallicity as well as surface gravity; a comparison of the spectra to those shown in Torres-Dodgen & Weaver (1993) indicates that these four stars could be high-metallicity K giants. However, the stars lie in the field giant region of the $J - H$, $H - K$ plot, and their CO strengths are also typical of field giants at their $J - K$ color.

Baade's Window (-3.9°)

For stars 4-136, 4-172, 4-205 and 4-269, the photometry, selected as described above, did not include a CO or H₂O measurement. However, each of these stars had another observation in which the K magnitude of the star differed from that chosen by less than 0.1 mag; the CO and H₂O measurements from these alternate observations were added to the photometry from which M_{bol} had determined by FBTW.

Also, the photometry for stars 4-093, 4-106 and 4-153 in TFW is not the same as that given in FBTW; the FBTW values were assumed to be correct. Star B-112 from TFW appears to actually be star 4-B112 and has therefore been assigned the corresponding photometry. In addition, Arp 1025 may in reality be Arp 1028, but insufficient evidence exists to constitute changing the designation; both stars are K giants. Star 4-B084 appears to be a binary - each of the three lines of its Ca II triplet shows two components.

The -8° Field

For the -8° M giants, the H₂O measurements were taken from TFW; FBTW presented truncated versions of the same data. Although star 8-029 is listed as a C star in Paper III, its spectrum is that of a typical M7+ giant.

The -10° Field

The unbiased infrared survey of this field is contaminated by a number of nearby field dwarfs. Stars 10-020, 10-021, 10-029, 10-039, 10-044, 10-054 and 10-107 all exhibit a strong Na I width, and those with low-resolution spectra also show other spectral indicators of late-type dwarfs - Ca I λ 6103, Ca I λ 6122, Ca I λ 6162, CaH with bandhead at 6385 Å, K I λ 7665 and K I λ 7699 (Turnshek *et al.* 1985). No photometry was taken for star 10-107, but the colors and/or CO strengths of the other six stars confirm that they are dwarfs. Stars 10-020 and 10-021 are the only two dwarfs which are not of spectral type M2 or later; they must be early M dwarfs, since they still show a significant Na I doublet. Note that Blanco spectral bin M2-4

is given for star 10-021 in Table 29 (FBTW); TFW listed 10-021 as an M5-6 star. Two additional stars were labelled field stars in FBTW, stars 10-032 and 10-035. They do have spectral types earlier than M2; the photometry shows that the former is probably a dwarf while the latter is a giant.

Star 10-023 appears to be a very high velocity star - the Ca II triplet of this star appears to be redshifted by about 350 km sec^{-1} .

The -12° Field

Several field dwarfs were present in the -12° infrared sample. In particular, Na I measurements indicate that stars 12-039, 12-047, 12-051, 12-061, 12-070 and 12-071 are M dwarfs, although 12-039 has a spectral type earlier than M2. The photometric data, when available, confirm these conclusions. Stars 12-030, 12-037 and 12-057 are too blue to be M stars; they appear to be earlier-type dwarfs. In addition, although they are not used in the modelling here, stars 12-041 and 12-048 may be worth further study; they show the same strong-lined characteristics seen in several of the stars sampled in the -3° field and are either supergiants or very metal-rich K giants.

4.3 The Baade's Window Model

As mentioned previously, the Baade's Window model was constructed first because Terndrup (1994, private communication) provided photometry of a field in BW. In this section, the three basic model input requirements - a CMD, an LF and calibration relations - are discussed with respect to BW. Also, an examination is made of the effects of varying the LF and/or the giant branch color-magnitude distribution of the

BW stars on the integrated colors and spectral indices of the model.

4.3.1 The Color-Magnitude Diagram

VI CCD photometry (Terndrup 1994; private communication) of the field surrounding the globular cluster NGC 6522 was used to construct a CMD for BW. Figure 24 shows the I_0 , $(V - I)_0$ diagram for stars lying more than $2.5'$ from the cluster center within a region having a total area of 39.7 arcmin^2 . This CMD has been corrected for extinction and reddening using the A_I and $E(V - I)$ values given in Table 7. The solid line in Figure 24 encloses the group of stars actually included in the basic BW model described below.

Fainter than $I_0 \sim 13$, Figure 24 consists primarily of two converging sequences of stars. The blue sequence extends from $(V - I)_0 \sim 0.3$, $I_0 \sim 13$ to fainter magnitudes and redder colors; it is made up of disk stars along the line of sight to BW. The redder, broader distribution of stars consists primarily of BW giant branch and asymptotic giant branch stars but undoubtedly includes some contamination by field stars and members of NGC 6522.

The Galactic bulge CMDs of T88 are morphologically similar to Figure 24. T88 attempted to remove the field star contamination from his CMDs using the Bahcall-Soneira (BS) model of the Galaxy (Bahcall 1986). However, he was forced to modify the predicted BS star counts to adequately reproduce the analogous blue disk sequences in his CMDs. This was necessary because the BS model assumes a smoothly varying exponential disk; recent evidence (*e.g.* Paczynski *et al.* 1994) indicates that the blue sequences in the CMDs actually consist of a spatially concentrated grouping

of stars, a spiral arm of the Milky Way, implying that the majority of these stars lie at approximately the same distance (~ 2 kpc) along the line of sight to BW. In other words, this branch represents the main-sequence of a spiral arm of the Milky Way.

Due to the inapplicability of the BS model, it was decided that an empirical removal of the field contamination was appropriate, and the following procedure was used to remove the disk star main sequence from Figure 24:

1. The stars in the CMD were binned in 0.25 mag. bins in I_0 and 0.1 mag. bins in $(V - I)_0$.
2. In each magnitude bin fainter than $I_0 = 13$, an attempt was made to fit a double or triple Gaussian distribution to the star counts as a function of color; the two most appropriate Gaussians were then assumed to represent the disk main-sequence and the BW giant branch. This fitting was performed using the interactive spectral line analysis program *LINER* (Pogge 1995, private communication). For each Gaussian, the central $(V - I)_0$ color, the full-width-at-half-maximum (FWHM) and the total number of enclosed stars was determined by *LINER*. Due to the merging of the BW and disk sequences in the CMD, the overall stellar distribution could only be resolved into two or more Gaussians for the bins with central magnitudes $I_0 = 13.125$ through $I_0 = 16.125$; the procedure was also successful for the bin centered at $I_0 = 17.625$, but the photometry is very incomplete at this magnitude. Figures 25 and 26 show the Gaussian fits for these bins. Note that the Gaussian fits for the magnitude bins fainter than $I_0 = 15.75$ are highly uncertain because the disk and bulge peaks are not fully

resolved.

3. Using the data provided by the Gaussian fits, various methods were explored for extrapolating the average disk star $(V - I)_0$ color, the FWHM of the disk distribution, the number of disk stars and the total star counts to fainter magnitudes. For this purpose, two methods for estimating the disk star counts were examined - using the number of stars bluer than $(V - I)_0 = 0.85$ or using the number of stars given by the Gaussian fitting. The total star counts was a simple sum of the stars within a given magnitude bin in the CMD. Figure 27 shows how these four parameters vary with magnitude; the linear relations shown are those used for the initial extrapolations. These lines represent a fit to the $I_0 = 13.125$ through $I_0 = 15.625$ bins for the average disk $(V - I)_0$ color, a constant FWHM for the disk star color distribution (FWHM = 0.26), a fit to the number of stars bluer than $(V - I)_0 = 0.85$ for $I_0 = 12.875$ through $I_0 = 15.125$ for the disk star counts, and a fit to the total star counts in the magnitude bins from $I_0 = 14.875$ through $I_0 = 16.875$.
4. For magnitude bins with $I_0 > 15.625$, these linear relations were extrapolated to facilitate removal of the disk star population in the CMD. First, the number of disk stars in each LF bin was estimated, and these stars were distributed in a Gaussian color distribution of the predicted average color and FWHM. The disk star counts were then binned in the same color bins used in the Gaussian fitting described above. If the extrapolated total number of stars was greater than the number actually observed for that LF bin, then the number of disk

- stars in each color bin was reduced by the inferred incompleteness factor.
5. Finally, the estimated number of disk stars were subtracted from the total CMD counts in each color-luminosity bin; if the number of disk stars to be removed was greater than the total number of stars contained in any bin, then that bin was assumed to contain no bulge stars.
  6. After this disk star removal, Gaussians were fit to the remaining stellar distribution to determine the average color of the BW stars in each magnitude bin. Figure 28 shows the Gaussian fits to the residual star counts after this approximate removal of the disk stars.
  7. The effects of the extrapolation procedures were examined by alternately varying each of the four extrapolation relations in Figure 27 while leaving the prediction scheme for the other three parameters unchanged. These variations included: (1) expanding the disk $(V - I)_0$ linear least-squares fit to incrementally include the points at $I_0 = 15.875$, 16.125 and 17.625 ; (2) estimating the disk star Gaussian FWHM from linear least-squares fits to the data from $I_0 = 13.125$ through $I_0 = 15.625$, 15.875 or 16.125 (but always excluding the points at $I_0 = 13.625$, 14.625 and 14.875); (3) fitting the disk star counts by linear least squares fits to the star counts given by the disk Gaussians (rather than the number of stars bluer than $(V - I)_0 = 0.85$) for $I_0 = 13.125$ through $I_0 = 15.625$, 15.875 and 16.125 ; and (4) eliminating the point at $I_0 = 14.875$ from the total star count fit.

Figure 29 compares the average color of the BW stars as a function of I_0 magnitude to isochrones from VandenBerg (1985). Because the disk and bulge star distributions are resolvable in the CMD for magnitude bins brighter than $I_0 = 15.5$, the open circles shown in this figure are the mean colors of the BW stars derived from Figures 25 and 26. The filled circles represent the central colors of the Gaussians fit to the stellar distribution in the CMD after correcting for the disk star contamination (see Figure 28); these colors are actually averages of the bluest and reddest $(V - I)_0$ colors which result when the extrapolation relations used to remove the disk star contamination are varied in all of the ways described above. The $(V - I)_0$ error bars on the filled points span the range of central colors found from these extrapolation variations.

The BW sequence appears to be most consistent with either a solar metallicity ($Z = 0.0169$), 6.0 Gyr isochrone or a slightly sub-solar metallicity ($Z = 0.0100$), 8.0 Gyr isochrone. Because it is more consistent with recent estimates of the age and metallicity of the stellar population in BW (see *e.g.* McWilliam & Rich 1994), the 8.0 Gyr, $Z = 0.010$ ($[\text{Fe}/\text{H}] = -0.23$) isochrone was chosen for use in the BW model as the fiducial sequence for the subgiant and main-sequence stars. However, note that this choice is heavily influenced by the agreement between the isochrone and BW subgiant branches and is, therefore, sensitive to the distance assumed to the Galactic bulge; $R_0 = 8.0$ kpc has been used here. The error bar on the $I_0 = 17.125$ point in Figure 29 represents the shift in the isochrone position if R_0 is varied by ± 1.0 kpc.

4.3.2 The I -band Luminosity Function

The empirical I -band LF for BW which results from the CMD of Figure 24 is shown in Figure 30. This LF represents the number of stars redder than $(V - I)_0 = 0.85$ for magnitude bins brighter than $I_0 = 15.25$, the number of stars enclosed in the Gaussian fits without any disk star removal for $I_0 = 15.375$ and $I_0 = 15.625$, and the number of stars enclosed in the Gaussian fits after correcting for disk star contamination for LF bins fainter than $I_0 = 15.75$. Also shown in Figure 30 is the BW LF presented by TFW, which has been estimated from their Figure 12, and a theoretical LF for an 8.0 Gyr $Z = 0.010$ population (Worthey 1994). The TFW LF has been revised to the extinction value used here, and the Worthey LF has been adjusted to $R_0 = 8.0$ kpc; the two LFs have also been rebinned to the binning scheme used for the LF derived from the CMD and normalized to the CMD star counts in the luminosity range $I_0 = 11 - 14$. The three LFs are in very good agreement for $I_0 < 16$, but the incompleteness of the VI photometry presented here causes the LF derived from Figure 24 to deviate from the others for $I_0 > 16$. The TFW and Worthey LFs remain similar to magnitudes as faint as $I_0 \sim 18.5$. Because the TFW LF is subject to incompleteness corrections and has been extrapolated to faint magnitudes, the I -band LF used in the modelling is a simple combination of the CMD LF (from Figure 24) for $I_0 < 15.25$ and the Worthey LF for $I_0 > 15.25$.

4.3.3 The Model Calibration Relations

The goal of the models is to simulate for the Galactic bulge the same integrated colors and spectral feature strengths measured for the early-type galaxies in Chapter 3. To review, the need for calibration relations is dictated by the fact that a full set of the necessary photometry ($V I J H K$, CO and H_2O) and red spectroscopy is not available for a complete sample of the stellar population in each of the Galactic bulge fields to be modelled. In addition, the adopted modelling strategy requires that the $(V - I)_0$ colors from the CMD first be transformed into $(H - K)_0$ colors and then uses the $(H - K)_0$ colors to derive the other photometric data and spectral indices.

Obviously, the critical calibration relation in the above process is that which converts the $(V - I)_0$ colors to $(H - K)_0$ colors. Fortunately, some of the BW stars studied by FW82 and FW87 have also been observed optically, thus allowing a relation between these two colors to be estimated for BW giants. Figure 31 shows the relationship between $(V - I)_0$ and $(H - K)_0$ for these BW giants and the calibration relation derived here and used in the Galactic bulge models. This $(V - I)_0$, $(H - K)_0$ calibration relation is made up of three line segments:

- a linear least-squares fit to the data for $(V - I)_0 < 1.60$ (which has not been constrained to pass through the origin because no stars bluer than $(V - I)_0 \sim 0.5$ appear in any of the bulge CMDs),
- a linear fit to the data with $1.60 < (V - I)_0 < 3.50$, which has been extended to $(V - I)_0 = 4.50$, and

- a linear segment extending redward from $(V - I)_0 = 4.50$, which has been guided by the predicted colors of $1 M_\odot$, solar metallicity Mira variables at minimum and maximum light (Bessell *et al.* 1989; hereafter BBSW) also shown in Figure 31.

In this and all further determinations of the calibration relations, the FW82 and FW87 stars which have colors or magnitudes placing them outside the boxed region of Figure 24 have been excluded from the fits. In Figure 31, the obvious outliers and all stars with $(H - K)_0 > 0.28$ (probable variables) have also been excluded; these data are enclosed in parentheses in the figure. Because the VI photometry of the BW stars is more uncertain than the infrared data, the distribution of the remaining stars was further examined for possible peculiarities. Due to this process, it was decided to also exclude the group of four stars lying near $(V - I)_0 \sim 2.2$, $(H - K)_0 \sim 0.23$ from the least-squares fitting; this decision was based upon the fact that the only star in this group for which a spectrum had been obtained shows anomalously high TiO absorption for its $(V - I)_0$ color.

Figure 31 also shows the relations between $(V - I)_0$ and $(H - K)_0$ for field giants and field dwarfs from Bessell & Brett (1988). Because the calibration relation derived here is not well-constrained for the K giants, it cannot be stated with certainty that it differs significantly from the field giant relation there. However, the change in the slope of the BW relation definitely occurs at a bluer color than it does for the field giants. This is consistent with the Ti enhancement seen in the BW giants (McWilliam & Rich 1994), with respect to solar abundance ratios, since TiO is the major source of differential blanketing between the V and I bands in these cool stars.

Once the $(V - I)_0$ to $(H - K)_0$ calibration relation had been defined, it was necessary to determine the calibration relations from which all of the other parameters could be derived. The first step in this process was predicting the $(I - K)_0$ color from $(H - K)_0$, and hence, since the I_0 magnitude is known, getting the K_0 magnitude. Figure 32 shows the $(H - K)_0$, $(I - K)_0$ diagram for the BW giants (FW) and the derived calibration relation between these two colors. As with the $(V - I)_0$, $(H - K)_0$ conversion, the relation between $(H - K)_0$ and $(I - K)_0$ consists of three line segments. The blue through red segments are, respectively, linear least-squares fits to the stars having $(I - K)_0 < 2.40$, those with $(I - K)_0 > 2.40$ and $0.19 \leq (H - K)_0 < 0.35$, and those redder than $(H - K)_0 > 0.35$. Figure 32 also compares the calibration relation derived here to the field giant and field dwarf relations given by Bessell & Brett (1988). In contrast to the trend seen in the $(V - I)_0$, $(H - K)_0$ diagram, the BW giants are systematically redder than the field giants in $(H - K)_0$ at all $(I - K)_0$ colors.

To determine the calibration relations between $(H - K)_0$ and the other infrared colors and between $(H - K)_0$ and the spectral indices the data for stars in the Sgr I field were combined with the BW sample. This was done for three reasons: (1) there is no VI CMD available for the Sgr I field, so it could not be modelled separately, (2) the Sgr I and BW stars are indistinguishable in the color-color and color-spectral feature diagrams, and (3) the number of BW giants having low-resolution spectra is small, so the calibration relations become much better defined by increasing the sample size. To determine the reddening of the stars in the Sgr I field, FTBW had

forced these stars to follow the same $S(7890)$, $(J - K)_0$ relation exhibited by the BW giants. Although an updated reddening has been used here for BW, the Sgr I giants actually show better agreement with the BW stars in this diagram than they did when the FTBW reddening estimate was used for BW; thus, the $E_0(B - V)$ value used here for the Sgr I field (see Table 7) is the same as that used by FTBW.

Figures 33 - 35 present the infrared photometry from FW82, FW87 and FTBW and the derived calibration relations between $(H - K)_0$ and $(J - H)_0$, $(H - K)_0$ and CO, and $(H - K)_0$ and H_2O , respectively; also shown are the relations for field giants and field dwarfs from Frogel *et al.* (1978). The calibration relations derived from these diagrams are polynomial fits to the data (excluding the LPVs and other outliers) and have been extended to redder and/or bluer colors by eye. The determination of the reddest portion of the $(J - H)_0$, $(H - K)_0$ relation was aided by the photometry (not shown) of Galactic bulge IRAS sources in a field between $b = -7^\circ$ and $b = -8^\circ$ from Whitelock *et al.* (1991).

In general, the bulge giants show the following tendencies with respect to field giants in the infrared: (1) the pre-M2 bulge giants appear similar to field giants in the $(J - H)_0$, $(H - K)_0$ diagram, while the M2+ giants are bluer in $(J - H)_0$ than field giants of the same $(H - K)_0$ color; and (2) the bulge giants have systematically stronger infrared CO bands and systematically weaker H_2O absorption than field giants of the same color. These trends are consistent with the bulge giants being hotter and more metal-rich than field giants of the same $(H - K)_0$.

Figure 36 shows the calibration relations for predicting the molecular band strengths from the $(H - K)_0$ colors. Most of the molecular band fits are again polynomials which have been subjectively extended to the red and/or blue; the I(8197) relation was partially fit by eye. The general trend exhibited by a given TiO band as a function of $(H - K)_0$ is for absorption to begin at a specific color, increase fairly quickly with redder colors and then approximately level off, although a more complicated behavior may actually apply after the band has saturated. The behavior of the I(8197) index with color is unusual and not understood at present; the drop in I(8197) for $(H - K)_0 > 0.24$ is probably caused by absorption in one of the continuum bands used to measure this feature rather than an actual weakening of the feature itself. In any case, this calibration relation is the least certain of those derived here.

Figure 37 compares the Galactic bulge molecular band index, $(H - K)_0$ calibration relations to the field star data. The lighter solid lines in this figure, which fit the field giant trends fairly well, represent the BW calibration relations shifted redward by 0.02 mag. in $(H - K)_0$. For all of the molecular bands but I(7450) and I(8197), the field dwarfs are fairly well fit by shifting the bulge relations redward by 0.09 mag. in $(H - K)_0$. However, the I(7450), $(H - K)_0$ relation for the field dwarfs redder than $(H - K)_0 = 0.184$ is a linear least-squares fit to the dwarfs with $(H - K)_0 > 0.18$. In addition, the field dwarf relation between $(H - K)_0$ and I(8197) was estimated by eye; it differs from the field giant relation in shape because the I(8197) index is affected by the strong Na I doublet in late-type dwarfs. Overall, though, the main difference between the TiO band strengths of Galactic bulge giants, field giants and

field dwarfs is the $(H - K)_0$ color at which TiO absorption is initiated.

The pseudo-equivalent widths of the atomic lines of the BW and Sgr I giants are plotted *vs.* $(H - K)_0$ in Figure 38. The calibration relations derived here and shown in this figure were all fit by eye; the relation for Ca8662 is simply the difference between the Ca II and Ca8542 relations. Note that the behavior of these line widths is extremely complicated, not only because the lines themselves may vary but also because the spectral regions used to measure the continuum are affected by TiO absorption and, therefore, also vary with color. Although negative indices are measured for many stars, these lines never truly appear in emission.

The atomic line widths of the field giants are compared to the bulge calibrations in Figure 39. For the Na I and Mg8807 features, the positions of the field giants do not appear to differ significantly from the Galactic bulge relations. However, the Ca II lines are more interesting. First, the Ca8542 index reaches a higher maximum strength in the field giants than in the BW/Sgr I giants; this would be consistent with the change in slope of the Ca8542, $(H - K)_0$ calibration relation for BW at $(H - K)_0 = 0.13$ being caused by increased absorption in the TiO band which overlies the Ca II triplet. Note that the field giants lying at higher Ca8542 than the BW calibration relation are all K-M1 giants, while the giants of this color in Figure 38 are M2+ giants. The difference in the Galactic bulge and field giants in Ca8662 is more difficult to interpret and is probably affected by a combination of factors: (1) the bulge giants are hotter than the field giants of the same $(H - K)_0$ color and therefore have a greater proportion of ionized calcium, (2) the bulge giants have a higher Ti/Fe

ratio (McWilliam & Rich 1994) than the field giants and thus have stronger TiO absorption at the same $(H - K)_0$ color, (3) the BW calibration relation between $(H - K)_0$ and Ca8662 was difficult to define due to the large scatter in Ca8662 (see Figure 38), and (4) the number of field giants observed with $(H - K)_0 < 0.13$ is low. All in all, a closer examination of the Ca II indices may be useful in clarifying some of the differences between Galactic bulge and nearby field stars.

Because Galactic bulge dwarf stars are inherently faint and difficult to observe, no photometry nor spectroscopy exists for a significant population of these stars. Thus, in the models, the bulge dwarfs have been assumed to follow the same color-color and color-spectral feature trends exhibited by local field dwarfs. These relationships between $(V - I)_0$ and $(H - K)_0$ and between $(V - I)_0$ and $(I - K)_0$ for dwarfs were taken from Bessell & Brett (1988) and are shown in Figures 31 and 32, respectively; the infrared photometric relations were taken from Frogel *et al.* (1978) and are presented in Figures 33, 34 and 35. The molecular band strength calibration relations used for bulge dwarfs are those shown as dotted lines in Figure 37.

To determine the dwarf star calibration relations between the strengths of the atomic lines and $(H - K)_0$, the observations of the field dwarfs contaminating the bulge star sample were used; because the measured pseudo-equivalent widths for atomic lines are sensitive to the spectral resolution of the data, only measurements from the aforementioned low-resolution spectra have been employed. The resulting field dwarf calibration relations, which were used to represent the Galactic bulge dwarfs in the modelling, are shown in Figure 40. All of these relations represent

linear least-squares regressions, omitting the designated data points. The Mg8807, $(H - K)_0$ calibration is a combination of two fits: one included the stars having $(H - K)_0 < 0.25$, and the other involved only the dwarfs with $(H - K)_0 > 0.20$. The Ca8498 relation is constant and equal to the median value of the data; the Ca II calibration relation is a sum of the Ca8542 and Ca8662 relations but does not differ appreciably from a true linear fit to the Ca II measurements.

4.3.4 The Basic Baade's Window Model

The basic BW model was built using the following pieces of information:

- for $I_0 < 15.25$, the individual stellar photometry for stars in the boxed area of Figure 24 and the resulting I -band LF were used,
- for $I_0 > 15.25$, the $\tau = 8.0$ Gyr, $Z = 0.0100$ VandenBerg (1985) isochrone (extended to $I_0 = 25$ by a linear extrapolation of the faintest two points tabulated by VandenBerg) and the Worthey (1994) LF were used,
- the subgiants were assumed to lie in the rectangular region of the CMD described by $(V - I)_0 = 0.65 - 0.90$ and $I_0 = 17.00 - 17.50$.
- for $I_0 > 15.25$, it was assumed that the color distribution of the stars was Gaussian with a FWHM of 0.35 mag., the approximate average indicated by the Gaussian fits to the BW giants in Figure 24;
- the calibration relations derived as described above and shown in Figures 31 through 40 were used; the colors and spectral indices of the subgiants were

linear interpolations between the values predicted for dwarf stars having the color of the blue edge of the subgiant region and the values predicted for giants having the color of the red edge of the subgiant region.

4.3.5 Uncertainties in the Basic Baade's Window Model

The uncertainties in the basic BW model were explored by altering three of the fundamental pieces of input data and examining the variations in the resulting integrated colors and spectral feature strengths. The following changes in the basic BW model were examined:

- substituting a ridge line for the BW giant branch, rather than using the stellar photometry,
- using a different I -band LF, and/or
- choosing different color and magnitude limits to define the subgiant region of the CMD.

It turned out that all reasonable choices of the limiting colors and luminosities of the subgiants produced identical integrated models. However, the other two types of variations require a more detailed discussion.

Because it was necessary to use giant branch ridge lines when modelling the -6° and -8° Galactic bulge fields, the differences between the ridge line and CMD models for BW, if significant, could illustrate possible systematic uncertainties in the model results for these other fields. To explore this effect, a BW giant branch ridge line was estimated from the $M_I, (V - I)_0$ ridge line presented in Figure 10 of T88; using the

$E(V - I)$, A_I and $(m - M)_0$ values from T88, this ridge line was transformed to the $V, V - I$ plane and overlaid on the CMD given in Figure 2(b) of T88. The small “kink” at $V \sim 17$ was removed to better match the distribution of stars in the T88 CMD, and this revised ridge line was then corrected for reddening and extinction, using the values adopted here for BW, and compared to the $(V - I)_0, I_0$ sequence predicted for the BW giant branch from the Gaussian fits described above.

The general shape of the resulting ridge line matched the CMD data fairly well, but the original ridge line was systematically bluer than the average giant branch colors derived from fitting Gaussians to the CMD of Figure 24. To align these two distributions, the revised T88 ridge line had to be shifted redward by 0.08 mag. in $(V - I)_0$. This revised and shifted T88 ridge line was then substituted into the BW model, replacing the individual stellar photometry. In addition, the FWHM used for the stellar distribution was systematically increased as the curvature of the ridge line increased at its bright end. The color-magnitude sequence used for this BW model is shown in Figure 41.

In addition to the switch from stellar photometry to a ridge line representation of the BW giant branch, specific changes in the I -band LF were explored. When the ridge line was used in the BW models, four different LF possibilities existed: the Worthey (1994) LF, the TFW LF and the two combinations in which the LF for $I_0 < 15.25$ was taken from the CMD of Figure 24 and merged with either the Worthey or TFW LFs. When the photometry from Figure 24 was used for the bright giants, only the latter two (combination) LFs were tested.

Table 30 names and defines the basic BW model and the five other BW models constructed here; Tables 31, 32 and 33 present the integrated colors, molecular band indices and atomic line indices, respectively, of these six models. Figures 42 through 47 show the results from the basic BW model and illustrate the effects of variations in the giant branch representation and/or LF on the colors and spectral feature strengths of the basic BW model. In these figures, each model is represented by the symbol corresponding to the model designation given in Table 30; also shown are the BW model predictions and average elliptical galaxy measurements from TFW.

In general, the following trends are evident from Figures 42 - 47:

- With a few notable exceptions (see next item), the BW models reproduce the colors and spectral feature strengths of a lower-luminosity elliptical galaxy nucleus.
- The model indices which do not fit the loci of the galaxy nuclei are H_2O , $\text{I}(7100)$ and $\text{S}(7890)$. Since no actual H_2O measurements exist for the Virgo galaxies observed here which are as blue as the BW models, it may be premature to conclude that there is an actual difference between the BW model predictions and the H_2O absorption in early-type galaxies. If the difference is real, it could be caused by the omission from the models of a few very red stars which are faint in the I band (see below). The model index $\text{I}(7100)$ is believed to be too strong because this TiO band lies much bluer than the I band; in determining its integrated strength, it would be more properly weighted by R -band magnitudes (see TFW for a discussion and resolution of this problem). The

model predictions for $S(7890)$ are too high because measurement of this index involves only one continuum band, and it is, therefore, sensitive to reddening. The $S(7890)$ strengths used in the calibration relations were not corrected for reddening, and the magnitude of this effect (TFW) is sufficient to account for the differences between the BW model predictions and the early-type galaxy measurements for $S(7890)$.

- Comparing models which differ only in the fainter parts of the LF, it is clear that varying the number of late-type dwarfs has a negligible effect on nearly all of the colors and indices (compare models c and C or models w and t).
- Replacing the stellar photometry of Figure 24 with the revised and shifted T88 ridge line tends to make colors bluer, CO weaker, H_2O much weaker, TiO bands stronger and atomic lines slightly stronger (compare models C and w and models c and t). This is believed to be due to two competing effects which can be discerned by visual inspection of the BW CMD. Figure 24 shows that the color-magnitude distribution of the stars in the BW field is actually quite complicated at the brightest magnitudes - for $I_0 < 13$, there exist at least two (and possibly three or four) different sequences of stars in the CMD. It is clear from this figure that two groups of stars are not well-represented by the T88 ridge line. First, the T88 ridge line omits some *very* red stars; these stars are not among the brightest in I_0 but would be the brightest stars in K_0 . They would have extremely strong CO, H_2O , TiO and VO absorption and weak Ca II lines. Overall, the effect of these stars would be substantial in the near-infrared but

not very large in the I -band and bluer; their omission would thus serve to make the model colors too blue and the model CO and H₂O indices too weak. Also, note that the brightest stars at I_0 tend to be bluer in $(V - I)_0$ in Figure 24 than the T88 ridge line. Although arguments can be made that these stars are not truly members of the BW stellar population, they are included in the models built from the CMD. Because these stars are the brightest at I_0 but relatively blue, they will have weaker TiO bands and stronger Ca II lines than the redder stars which the T88 ridge line predicts. Their omission increases the TiO band strengths and makes colors redder.

- The differences between the models incorporating the revised and shifted T88 ridge line but using different LFs are almost entirely due to the LF differences for $I_0 < 11.5$. Due to the curvature and turnover of the T88 ridge line, it was only extended as bright as $I_0 = 11.375$; for any given LF, all brighter stars were included in this brightest bin when the T88 ridge line was used in the model. In moving from the w and t models to the W model and then to the T model, the number of stars in the brightest LF bin steadily increases; when models were constructed which simply omitted the brightest LF bin, the w, t, W and T models did not significantly differ in any of the color-color or color-spectral feature diagrams. It is interesting to note that simply increasing the number of stars in the brightest LF bin also tends to move the models *along* the trends which the early-type galaxy nuclei follow.

- Under no circumstances do the BW models built here reproduce the results of TFW; a further discussion of these model differences is postponed until Chapter 5.

4.3.6 Models of the Bulge as a Function of Radius

To model the integrated light of the stellar population in the -6° and -8° fields, the same basic pieces of information used to model BW were required - a CMD, a LF and calibration relations. The following section describes how these pieces of information were derived for the higher latitude fields.

Changes to the Baade's Window Models

For the -6° and -8° fields, no new VI photometry was available. Thus, as described for BW above, giant branch ridge lines were estimated from Figure 10 of T88 and compared to his V , $V - I$ CMDs (his Figures 3(b) and 4(b), respectively). Each of these ridge lines represented the average distribution of stars in the respective CMD quite well, so their general shapes were not revised from T88. However, because the T88 ridge line for BW required a redward shift of 0.08 mag. to best match the giant branch in Figure 24, a similar shift was applied to the -6° and -8° ridge lines as well. However, this shift caused the -6° ridge line to cross over the BW ridge line, being bluer than BW at its base but redder at its tip. Therefore, the -6° giant branch was adjusted to merge smoothly with that of BW at the bright end.

To determine the average color-magnitude relation for the dwarfs and subgiants in these fields, the -6° and -8° ridge lines were compared to isochrones from Vanden-

Berg (1985). Because disk star contamination inhibited an accurate determination of the luminosity of the base of the giant branch in the CMDs of T88, choosing the isochrones which best aligned with the -6° and -8° giant branch ridge lines was somewhat subjective; the isochrone which appeared to merge most smoothly with the ridge line at some point near its faint end was eventually chosen to best represent the fainter part of the stellar population. Since the ridge lines became bluer in $(V - I)_0$ with increasing latitude, it was assumed that the shift in the giant branch color between bulge fields was due to a change in either the average age or average metallicity of the stellar population.

Thus, the ridge lines were first compared to younger isochrones having the same metallicity as the BW isochrone ($Z = 0.0100$). The -6° and -8° ridge lines turned out to merge quite well with 7.0 Gyr and 6.0 Gyr isochrones, respectively. However, because the faint ends of the ridge lines did not lie exactly on the isochrones, the bright ends of the isochrones were simply connected to the second faintest ridge line points to delineate the average color-magnitude trend of the stars in each field. Linear interpolations were then performed to determine the average colors appropriate to the LF bins used in the BW models.

Next, the -6° and -8° ridge lines were compared to 8.0 Gyr isochrones of different metallicity, and their faint ends each lay between the $Z = 0.0100$ and next most metal-poor isochrone ($Z = 0.0060$); interpolation between these two isochrones was required. These interpolations were made by assuming that: (1) the $(V - I)_0$ color of the interpolated isochrone at $I_0 = 16.625$ was the same as that of the color-magnitude

sequence which resulted when the ridge line color shifts were assumed to be caused by age variations, and (2) the blueward shift in color was the same percentage of the color difference between the two isochrones at all luminosities. The resulting -6° and -8° interpolations represented $Z = 0.0092$ ($[\text{Fe}/\text{H}] = -0.26$) and $Z = 0.0084$ ($[\text{Fe}/\text{H}] = -0.30$) isochrones, respectively.

The color-magnitude sequences used to model the -6° and -8° Galactic bulge fields are shown in Figure 48, where they are also compared to the BW model sequence. These sequences incorporate the same FWHM pattern as that used for BW.

FTBW showed that the bolometric (and K -band) LF is the same in the -6° and -8° fields as in BW. Because there exists no independent evidence to suggest otherwise, the I -band LF was assumed to be the same in these three fields as well. Thus, the merged CMD/Worthey LF used in the basic BW model was also used to model the higher latitude Galactic bulge fields.

Unfortunately, there are no stars in the -6° or -8° fields for which both optical and infrared photometry are available. Thus, there is no way to determine whether the stars in these fields follow the same $(V - I)_0$, $(H - K)_0$ and $(H - K)_0$, $(I - K)_0$ relations as the BW giants. For this reason, the BW calibration relations have been used for these two cases.

Figure 49 shows the trends in the infrared photometry for giants in the -6° and -8° fields; all of this data comes from FTBW and has been adjusted to the reddening and extinction values used here. Figures 50 and 51 show the relationships between $(H - K)_0$ and the molecular band indices for the -6° and -8° giants, respectively;

Figures 52 and 53 are similar plots for the atomic line pseudo-equivalent widths. Also shown in all of these figures are the calibration relations derived from BW stars; Figure 49 shows the trends exhibited by field giants and field dwarfs as well.

In general, the giants in the -6° and -8° fields follow the BW calibration relations, but this was examined more closely by determining the average and median offset of the -6° and -8° stars from the BW calibrations involving $(J - H)_0$, CO, H_2O , I(7100), I(7890), S(7890) and I(8460). In general, it was assumed that, if the calibration relations varied as a function of galactic latitude, these variations would involve simple shifts of the relations in one of the two parameters, leaving the general shapes of the calibrations unchanged. Also, since the bulge stars tended to spread out between the BW and field trends, the offsets were assumed to lie in the approximate direction of the field giant relations. For this reason, the offsets were determined in the sense $\delta(J - H)_0$ for the $(J - H)_0$, $(H - K)_0$ relation, δCO for the CO *vs.* $(H - K)_0$ relation and $\delta(H - K)_0$ for the other relations.

To compute the offsets, an initial average offset was determined for all of the stars within a given color range. Since the 1σ measurement uncertainties in all of the photometry were estimated to be ± 0.02 mag. by FW82, FW87 and FTBW, any points lying more than 0.06 mag. from this mean were then thrown out, and the new mean offset was found. All stars within ± 0.06 mag. of this mean value (including those thrown out previously) were used to reiterate this process until a consistent mean offset was determined. Table 34 presents the resulting offsets for the -6° and -8° fields. For reference, the offsets are also presented for the Sgr I and BW giants

used to define the calibration relations, for the field giants observed by FW87 and TFW and for the field dwarfs discovered in the surveys of Galactic bulge M2+ giants. Since the average offsets for the -6° and -8° fields are generally comparable to those of the Sgr I and BW stars used to define the calibration relations (and comparatively less than the average offsets of the field stars), it was decided that the same calibration relations used in the BW models would be used when modelling the -6° and -8° fields.

Results

The colors and spectral feature strengths resulting from the -6° and -8° models are presented in Tables 35 - 37 and shown in Figures 54 through 59, where they are compared to the general trends exhibited by the Virgo galaxies discussed in Chapter 3. In general, the radial trends in the Galactic bulge appear similar in slope to the relations exhibited by the early-type galaxy nuclei as a function of color. However, this will be explored more fully and some of the deeper implications of these model results will be discussed in Chapter 5; only three notable exceptions to the model/galaxy agreement will be briefly discussed here.

First, the H_2O indices predicted by the models have much lower strengths than any of those observed in the galaxy nuclei. Since the model colors are bluer than any of the observed galaxies, it may be premature to conclude that the model H_2O value is actually too low. However, assuming that the model H_2O is too weak, then it is believed to be due to the omission of a few very red stars from the model which may be present in the galaxies. These stars would be among the brightest in K but not in

I , due to the curvature of the giant branch in I_0 . Thus, they would only produce a noticeable effect on the near-infrared parameters, particularly the H_2O bands, which are extremely strong in the reddest stars. The effect of neglecting to include these stars can be seen by comparing models c and C in Figures 42(d) and 43(c) to the other models. Models t , T , w and W have substantially weaker H_2O than models c and C because the reddest stars in Figure 24 are omitted when a ridge line is used to represent the BW giant branch in the models.

Also, the $I(7100)$ and $S(7890)$ bands are much weaker in the galaxy nuclei than the models predict. TFW noted this same problem for $I(7100)$; it is caused by the weighting of the individual $I(7100)$ indices by the I -band magnitudes in determining the integrated $I(7100)$ strength. A more proper weighting would use a magnitude more representative of the flux near $7100 \text{ \AA}$; R -band magnitudes would be better but not ideal (see TFW). The reduced flux in the R -band (as compared to I) due to the cool temperatures and differential blanketing in the stars containing TiO absorption would serve to reduce the $I(7100)$ indices predicted by the models. The $S(7890)$ discrepancy is due to the fact that $S(7890)$ is measured with only one continuum band and is, therefore, sensitive to reddening; the differences between the models and observations for $S(7890)$ are consistent with those expected when this reddening dependence is ignored (TFW).

Table 7: The Extinction and Reddening of the Galactic Bulge Fields

	Sgr I Field	Baade's Window	-6° Field	-8° Field
$E_0(B - V)$	0.57 ^a	0.51 ^b	0.41 ^c	0.25 ^d
A_I	...	1.06	0.86	0.52
A_K	0.16	0.14	0.11	0.07
$E(V - I)$	...	0.57	0.46	0.28
$E(J - K)$	0.31	0.28	0.22	0.14
$E(H - K)$	0.11	0.10	0.08	0.05
$E(CO)$	-0.020	-0.020	-0.015	-0.010
$E(H_2O)$	0.030	0.030	0.020	0.015

^aderived as described in the text^bWalker & Terndrup (1991); Terndrup & Walker (1994)^cZinn (1980)^dvan den Bergh & Herbst (1974)

Table 8: The Molecular Band Indices of the M2+ Giants in the Sgr I Field

Star	Blanco ^a Bin	MK ^b Bin	I(7100)	I(7450)	I(7890)	S(7890)	I(8197)	I(8460)
3A-01	...	5	1.021	-0.059	0.751	0.891	0.053	0.485
3A-05	...	7	1.300	0.066	1.146	1.431	0.143	0.660
3A-09	...	7	0.970	0.059	1.024	1.300	-0.007	0.640
3A-10	...	7	1.154	0.161	1.159	1.483	0.081	0.702
3A-13	...	7	1.037	-0.031	0.904	1.099	-0.014	0.565
3A-16	...	7	0.793	0.001	0.916	1.150	0.002	0.581
3-001	2	2	0.599	-0.022	0.169	0.219	0.044	0.092
3-003	5	5	0.892	-0.060	0.474	0.572	0.045	0.307
3-012	2	2	0.717	-0.048	0.320	0.368	0.039	0.197
3-013	7V	7V	0.931	0.374	1.202	1.627	-0.027	0.831
3-016	5	7	1.075	0.273	1.223	1.609	0.129	0.774
3-021	5	2	0.247	-0.004	0.048	0.099	0.028	0.026
3-023	2	2	0.267	-0.011	0.057	0.113	0.031	0.034
3-030	7V	5V	1.048	-0.038	0.590	0.729	0.026	0.453
3-031	5	5	0.749	-0.043	0.739	0.895	0.077	0.481
3-033	2	2	0.643	-0.042	0.217	0.297	0.030	0.153
3-035	7	7	1.074	-0.017	0.972	1.185	0.000	0.591
3-039	7	7	1.103	0.040	1.063	1.324	0.023	0.680
3-046	5	7	1.081	-0.017	0.985	1.207	0.058	0.631
3-052	5	7	1.287	-0.033	0.967	1.178	0.081	0.648
3-060	2	7	0.616	0.073	0.883	1.166	-0.030	0.551
3-064	5	7	1.083	-0.037	0.916	1.107	0.049	0.576
3-068	2	2	0.371	-0.013	0.137	0.167	0.039	0.069
3-075	5	2	0.843	-0.046	0.309	0.379	0.032	0.167
3-080	5	5	1.022	-0.070	0.789	0.939	-0.010	0.488
3-084	5	7	1.108	-0.058	0.890	1.073	-0.006	0.566
3-086	2	2	0.301	-0.008	0.061	0.103	0.017	0.020
3-092	5	2	0.824	-0.063	0.449	0.548	0.020	0.285
3-103	5	2	0.858	-0.058	0.408	0.485	0.038	0.231
3-109	5	2	0.288	-0.005	0.039	0.105	0.021	0.018
3-113	5	7	1.079	0.027	1.103	1.358	-0.042	0.639
3-118	5	2	0.511	-0.048	0.230	0.284	0.039	0.135
3-123	2	2	0.486	-0.038	0.234	0.288	0.014	0.129
3-127	7	7	1.257	0.071	1.165	1.462	0.113	0.694
3-138	5	2	0.415	-0.026	0.158	0.198	0.017	0.087
3-140	5	5	0.524	0.083	0.796	1.051	-0.014	0.470
3-141	5	7	0.749	0.016	0.927	1.154	-0.079	0.517
3-144	5	2	0.454	-0.025	0.145	0.207	0.005	0.075
3-145	5	7	1.281	0.006	0.879	1.066	-0.031	0.574
3-146	5	2	0.672	-0.056	0.261	0.333	-0.012	0.152
3-148	2	2	0.360	-0.013	0.105	0.139	0.016	0.050
3-149	5	2	0.606	-0.039	0.257	0.315	0.021	0.158
3-150	5	2	0.496	-0.018	0.160	0.201	0.038	0.090
3-151	2	2	0.437	-0.022	0.114	0.150	0.029	0.054
3-152	5	2	0.679	-0.054	0.301	0.373	0.003	0.166

^aspectral type bin taken from Frogel *et al.* (1990); 0=K-M1, 2=M2-4, 5=M5-6, 7=M7+^bspectral type bin derived from TiO band strength (see text)

Table 9: The Atomic Line Indices of the M2+ Giants in the Sgr I Field

Star	Na I	Mg8807	Ca8498	Ca8542	Ca 8662	Ca II
3A-01	-1.13	-0.02	-3.45	0.27	2.84	3.10
3A-05	0.46	-1.68	-10.34	-5.12	3.98	-1.14
3A-09	-5.49	-0.13	-9.47	-3.31	2.99	-0.32
3A-10	-2.36	-0.91	-10.26	-4.64	3.80	-0.83
3A-13	-4.00	-0.11	-6.43	-0.59	2.65	2.06
3A-16	-4.44	-0.05	-7.78	-2.20	3.05	0.85
3-001	1.21	0.34	1.45	4.31	3.97	8.27
3-003	-0.50	0.29	0.06	3.55	2.45	6.00
3-012	-0.39	0.43	0.77	3.59	2.83	6.42
3-013	-6.71	-0.26	-4.97	-2.01	3.79	1.78
3-016	-0.83	-1.44	-7.16	-3.71	3.95	0.23
3-021	0.06	0.43	0.72	4.10	2.88	6.98
3-023	0.11	0.59	1.29	4.17	3.14	7.31
3-030	-1.59	0.15	-1.62	0.85	0.46	1.31
3-031	-0.61	0.08	-3.46	0.53	3.19	3.72
3-033	0.05	0.38	1.19	3.78	3.09	6.87
3-035	-4.09	-0.27	-8.78	-2.82	2.50	-0.32
3-039	-3.81	-0.29	-11.01	-3.82	3.22	-0.60
3-046	-2.86	-0.20	-7.80	-2.09	3.55	1.46
3-052	-1.03	-0.56	-5.78	-1.12	3.05	1.94
3-060	-5.74	-0.34	-7.40	-2.57	2.85	0.28
3-064	-2.46	-0.27	-5.82	-1.22	3.14	1.93
3-068	0.39	0.53	1.69	4.67	3.61	8.28
3-075	0.75	-0.12	2.16	3.95	4.12	8.07
3-080	-3.37	0.18	-3.50	1.25	2.57	3.82
3-084	-3.77	0.10	-6.29	-0.89	2.23	1.34
3-086	0.50	0.89	1.46	4.84	3.74	8.58
3-092	-1.12	0.57	-0.40	3.73	2.60	6.33
3-103	-0.23	0.06	-0.53	2.82	2.13	4.95
3-109	0.55	0.41	1.28	3.67	3.37	7.04
3-113	-5.70	-0.39	-13.95	-5.45	2.58	-2.87
3-118	0.46	0.19	-0.04	3.13	2.69	5.82
3-123	-0.57	-0.12	-0.34	2.91	1.61	4.52
3-127	-1.53	-1.35	-12.43	-5.48	3.75	-1.73
3-138	0.10	0.28	0.58	4.12	3.34	7.46
3-140	-4.01	-0.13	-5.74	-2.10	2.85	0.75
3-141	-5.16	-0.48	-10.68	-4.18	2.19	-2.00
3-144	-0.43	-0.07	-0.55	2.74	2.15	4.89
3-145	-3.80	-0.08	-4.72	0.05	1.84	1.89
3-146	-1.09	-0.04	-0.89	2.08	1.47	3.56
3-148	-0.34	-0.25	-0.43	2.83	1.40	4.23
3-149	-0.02	0.37	0.38	3.60	3.07	6.67
3-150	0.89	0.70	1.14	4.26	3.16	7.42
3-151	0.98	0.47	0.97	4.48	3.15	7.63
3-152	-0.54	0.26	-0.33	3.37	1.97	5.34

Table 10: The Molecular Band Indices of the K-M1 Giants in the Sgr I Field

Star	Blanco ^a Bin	MK ^b Bin	I(7100)	I(7450)	I(7890)	S(7890)	I(8197)	I(8460)
3-007	2	0	-0.005	0.006	-0.009	-0.043	0.024	-0.005
3-048	2	0	0.305	0.005	0.052	0.077	0.035	0.029
3-055	2	0	-0.004	0.007	0.002	-0.029	0.004	-0.007
3-093	2	0	0.010	0.005	-0.009	-0.022	0.012	-0.020
3-099	2	0	0.087	0.008	-0.004	0.035	0.011	-0.008
3-133	5	0	0.008	0.001	-0.011	0.007	0.009	0.004
3-137	2	0	0.010	-0.002	-0.006	-0.020	0.003	-0.002
3-142	2	0	0.089	-0.003	0.003	0.054	0.005	0.003
3-143	2	0	0.067	0.004	-0.004	0.002	0.008	0.006
3-147	2	0	0.011	0.008	-0.009	-0.040	0.010	-0.006

^aspectral type bin taken from Frogel *et al.* (1990); 0=K-M1, 2=M2-4, 5=M5-6, 7=M7+

^bspectral type bin derived from TiO band strength (see text)

Table 11: The Atomic Line Indices of the K-M1 Giants in the Sgr I Field

Star	Na I	Mg8807	Ca8498	Ca8542	Ca 8662	Ca II
3-007	0.27	0.49	1.00	3.78	3.04	6.82
3-048	0.25	0.66	1.53	4.47	3.94	8.41
3-055	0.60	0.38	1.44	3.28	2.68	5.95
3-093	-0.10	0.95	1.14	3.44	2.94	6.38
3-099	0.16	0.64	1.19	3.52	3.24	6.76
3-133	-0.18	-0.10	-0.23	2.28	1.94	4.21
3-137	-0.01	0.06	0.34	3.14	2.59	5.73
3-142	-0.12	0.06	0.28	2.81	2.35	5.16
3-143	0.26	0.44	0.77	3.82	3.07	6.89
3-147	0.24	0.64	0.77	3.76	3.09	6.86

Table 12: The Molecular Band Indices of the M2+ Giants in Baade's Window

Star	Blanco ^a Bin	MK ^b Bin	I(7100)	I(7450)	I(7890)	S(7890)	I(8197)	I(8460)
4-039	7	7V	1.431	0.189	1.145	1.458	0.018	0.885
4-054	7	7V	1.286	0.325	1.179	1.558	0.070	0.857
4-055	7V	7V	1.109	0.283	1.182	1.563	-0.073	0.689
4-063	7	7V	1.187	0.139	1.016	1.310	-0.035	0.594
4-087	7	7V	1.148	0.710	1.514	2.025	-0.128	0.961
4-093	5	5	...	...	...	0.950	0.055	0.537
4-095	5	5	...	...	...	0.689	0.035	0.392
4-098	5	5	1.000	-0.080	0.712	0.840	0.022	0.444
4-099	5	5	1.106	-0.067	0.742	0.881	0.076	0.476
4-106	5	5	...	...	...	0.981	0.027	0.500
4-111	7	7	...	...	...	1.361	0.102	0.674
4-117	7	5	...	...	...	0.823	0.002	0.414
4-120	7V	7V	0.810	0.202	1.081	1.429	-0.073	0.617
4-123	7	7	1.240	0.096	1.129	1.436	0.039	0.675
4-127	7V	7V	1.076	0.051	1.095	1.359	-0.024	0.653
4-133	5	5	1.032	-0.070	0.600	0.718	0.062	0.405
4-134	7	7	0.452	0.070	0.797	1.057	0.063	0.489
4-138	5	2	0.824	-0.065	0.410	0.486	0.030	0.269
4-139	7V	7V	1.241	0.360	1.214	1.614	0.027	0.727
4-142	7	7	...	...	...	1.613	-0.004	0.715
4-153	5	7V	1.189	0.014	0.744	0.921	0.036	0.511
4-172	7V	7V	1.148	0.334	1.150	1.540	0.078	0.653
4-179	7	7	1.301	0.259	1.181	1.555	0.066	0.756
4-180	5	5	0.533	-0.052	0.639	0.760	-0.028	0.362
4-181	7	7	...	...	...	1.351	0.039	0.698
4-200	5	2	0.762	-0.054	0.288	0.359	0.036	0.183
4-205	7	7	...	...	...	1.474	-0.043	0.600
4-208	7	7V	0.425	0.144	0.890	1.189	-0.074	0.584
4-228	5	5	0.979	-0.078	0.531	0.646	0.021	0.348
4-239	5V	7V	1.257	0.145	1.182	1.504	-0.017	0.752
4-248	7V	7V	1.199	0.216	1.123	1.484	-0.129	0.619
4-250	7	7V	1.968	0.710	1.524	2.032	-0.069	0.992
4-269	7	7	0.705	0.081	0.942	1.211	-0.049	0.557
4-289	7	7	1.264	0.299	1.210	1.595	0.073	0.757
4-301	7	7V	1.485	0.268	1.310	1.675	-0.032	1.019
4-B001	0	2	...	...	...	0.104	0.017	0.057
4-B012	2	2	...	...	...	0.158	0.007	0.063
4-B061	5	2	...	...	...	0.373	0.027	0.191
4-B064	2	2	...	...	...	0.233	0.055	0.059
4-B066	2	2	...	...	...	0.120	0.010	0.042
4-B083	5	5	...	...	...	0.567	0.058	0.297
4-B084	5	2	...	...	...	0.133	0.014	0.055
4-B094	5	2	...	...	...	0.149	0.032	0.064
4-B112	2	2	0.607	-0.035	0.183	0.232	0.015	0.089
4-B116	2	2	...	...	...	0.466	0.039	0.239
4-B143	2	2	0.419	-0.026	0.105	0.147	0.035	0.066
4-B158	2	2	...	...	...	0.113	0.029	0.030
TLE 120	V	7V	1.490	0.187	1.093	1.381	0.059	0.843
TLE 426	V	7V	0.919	0.510	1.278	1.746	0.031	0.723

^aspectral type bin taken from Frogel & Whitford (1987); 0=K-M1, 2=M2-4, 5=M5-6, 7=M7+^bspectral type bin derived from TiO band strength (see text)

Table 13: The Atomic Line Indices of the M2+ Giants in Baade's Window

Star	Na I	Mg8807	Ca8498	Ca8542	Ca 8662	Ca II
4-039	-4.48	-0.35	-6.40	-1.75	2.28	0.53
4-054	-1.15	-1.03	-4.40	-2.44	3.74	1.31
4-055	-6.77	0.00	-6.22	-2.45	2.78	0.33
4-063	-4.50	-0.12	-7.60	-3.07	2.00	-1.06
4-087	-7.81	-0.23	-4.22	-1.76	4.22	2.46
4-093	-0.97	-0.58	-1.68	1.49	2.68	4.18
4-095	-0.95	-0.51	-0.61	2.61	1.81	4.41
4-098	-1.97	0.33	-2.71	1.80	2.89	4.70
4-099	0.55	-0.27	-1.30	1.44	3.57	5.00
4-106	-3.72	-1.14	-2.88	1.39	1.94	3.32
4-111	-1.11	-0.84	-9.12	-3.93	3.46	-0.47
4-117	-2.47	0.06	-1.37	3.00	1.54	4.54
4-120	-6.02	-0.43	-7.12	-3.19	2.42	-0.77
4-123	-3.25	-0.11	-10.11	-3.79	3.42	-0.37
4-127	-5.09	-0.16	-10.29	-4.19	3.19	-1.01
4-133	-0.37	0.59	-0.46	2.87	2.84	5.72
4-134	-1.99	-0.27	-6.00	-1.89	3.64	1.75
4-138	-0.62	0.79	0.58	4.14	2.83	6.97
4-139	-3.43	-0.68	-5.78	-2.76	3.38	0.63
4-142	-5.84	-0.65	-6.05	-3.17	1.53	-1.64
4-153	-1.17	0.14	-2.57	0.52	1.28	1.80
4-172	-0.84	-0.97	-4.51	-2.28	3.59	1.30
4-179	-2.51	-0.31	-6.38	-2.32	3.45	1.13
4-180	-2.65	-0.17	-4.09	0.31	1.96	2.27
4-181	-4.05	-0.74	-7.42	-2.34	2.36	0.02
4-200	0.42	0.49	1.87	4.13	3.49	7.62
4-205	-7.13	-0.21	-5.42	-1.64	2.50	0.86
4-208	-5.84	-0.26	-6.56	-2.57	1.94	-0.63
4-228	-1.53	0.35	-0.65	2.94	2.39	5.33
4-239	-6.60	-0.23	-11.75	-4.77	3.28	-1.49
4-248	-6.99	0.03	-6.83	-3.32	2.00	-1.33
4-250	-6.79	-0.09	-3.41	-1.19	3.29	2.10
4-269	-5.71	-0.13	-8.05	-2.75	2.63	-0.12
4-289	-2.14	-0.40	-6.25	-3.16	3.16	-0.01
4-301	-7.16	-0.34	-9.38	-2.75	2.90	0.16
4-B001	-0.46	0.19	1.35	4.29	2.95	7.24
4-B012	-1.08	0.56	1.14	4.35	2.64	7.00
4-B061	-0.49	0.63	1.33	4.11	2.67	6.78
4-B064	0.20	-0.02	1.18	5.18	2.29	7.46
4-B066	-0.28	0.76	1.03	4.36	3.30	7.66
4-B083	-0.01	0.82	0.23	3.57	2.16	5.73
4-B084	0.24	0.28	0.92	3.88	2.91	6.79
4-B094	-0.34	0.61	0.52	4.49	3.02	7.51
4-B112	0.69	0.67	1.46	4.18	3.77	7.95
4-B116	-1.19	0.71	-0.29	3.57	2.59	6.16
4-B143	0.17	0.90	1.77	4.87	3.15	8.02
4-B158	-0.49	0.26	1.18	4.62	2.68	7.30
TLE 120	-2.46	-0.50	-5.71	-2.32	2.22	-0.09
TLE 426	-3.39	-0.29	-2.92	-1.97	3.14	1.16

Table 14: The Molecular Band Indices of the K-M1 Giants in Baade's Window

Star	Blanco ^a Bin	MK ^b Bin	I(7100)	I(7450)	I(7890)	S(7890)	I(8197)	I(8460)
4-B005	0	0	...	...	...	0.013	0.025	0.036
4-B042	2	0	...	...	...	0.037	0.017	-0.014
4-B068	2	0	...	...	...	0.057	0.002	0.023
4-B078	2	0	...	...	...	0.058	0.012	0.015
4-B095	0	0	...	...	...	0.060	0.021	-0.022
4-B096	2	0	...	...	...	0.033	0.029	-0.001
4-B109	0	0	...	...	...	0.015	0.027	-0.028
4-B121	0	0	0.098	0.007	0.006	0.020	0.011	0.006
4-B136	2	0	...	...	...	0.050	0.022	0.005
4-B160	2	0	0.107	-0.008	0.001	0.046	0.020	-0.004
Arp 1025	...	0	0.026	-0.006	-0.002	-0.020	0.037	-0.009
Arp 1039	...	0	0.023	0.005	-0.024	-0.033	0.031	-0.003
Arp 1053	...	0	-0.003	-0.008	-0.009	0.003	-0.003	-0.006
Arp 1064	0	0	...	...	...	0.086	0.052	0.006
Arp 1076	0	0	...	...	...	0.023	0.031	-0.013
Arp 1145	0	0	...	...	...	0.025	0.025	-0.008
Arp 1202	0	0	0.056	0.011	0.013	0.007	0.010	0.008
Arp 1320	...	0	0.264	-0.007	0.044	0.080	0.035	0.019
Arp 1322	...	0	-0.005	0.008	-0.006	0.008	0.020	-0.026
Arp 2146	...	0	-0.013	0.005	-0.008	-0.018	0.023	-0.022
Arp 2240	...	0	0.005	0.005	-0.007	-0.021	0.028	-0.004
Arp 2244	...	0	0.010	0.003	-0.001	0.027	-0.001	-0.036
Arp 3106	...	0	-0.006	-0.005	-0.007	0.016	0.017	-0.022
Arp 3164	...	0	0.006	0.007	0.007	0.028	0.019	-0.024
Arp 3209	0	0	0.039	0.013	-0.007	-0.001	0.018	-0.030
Arp 4003	...	0	-0.013	0.011	0.012	0.030	0.011	-0.011
Arp 4025	...	0	-0.001	0.018	0.015	0.016	0.037	-0.021
Arp 4329	...	0	-0.009	-0.003	-0.013	0.005	0.016	-0.004

^aspectral type bin taken from Frogel & Whitford (1987); 0=K-M1, 2=M2-4, 5=M5-6, 7=M7+^bspectral type bin derived from TiO band strength (see text)

Table 15: The Atomic Line Indices of the K-M1 Giants in Baade's Window

Star	Na I	Mg8807	Ca8498	Ca8542	Ca 8662	Ca II
4-B005	-0.40	0.57	1.04	5.27	3.56	8.84
4-B042	-1.00	0.63	1.39	4.01	2.87	6.88
4-B068	-0.18	0.51	1.66	4.58	3.10	7.68
4-B078	0.02	0.84	0.96	4.00	3.36	7.36
4-B095	-0.21	1.24	0.61	4.19	1.90	6.08
4-B096	1.20	0.89	1.20	5.00	3.04	8.03
4-B109	0.92	0.86	1.40	4.42	2.95	7.37
4-B121	0.13	0.73	1.36	3.99	3.36	7.36
4-B136	0.36	1.53	0.94	5.02	2.97	8.00
4-B160	-0.18	0.71	1.57	4.20	2.92	7.12
Arp 1025	0.42	0.64	0.35	3.67	3.34	7.01
Arp 1039	0.66	0.56	1.20	4.65	2.96	7.61
Arp 1053	-0.52	0.14	1.19	3.06	2.98	6.04
Arp 1064	1.03	0.33	1.04	4.28	3.41	7.68
Arp 1076	0.70	1.24	0.66	4.48	2.76	7.24
Arp 1145	0.16	0.44	0.89	3.56	2.61	6.17
Arp 1202	0.88	0.75	1.64	4.23	3.24	7.47
Arp 1320	0.47	1.00	1.20	4.97	3.14	8.12
Arp 1322	0.63	0.71	1.34	3.95	3.49	7.44
Arp 2146	0.69	-0.09	1.69	4.71	3.68	8.39
Arp 2240	0.30	0.72	0.96	3.68	2.29	5.98
Arp 2244	0.07	0.40	1.47	4.34	3.53	7.88
Arp 3106	0.23	0.11	0.66	2.50	2.63	5.13
Arp 3164	0.46	0.77	1.30	3.79	2.71	6.50
Arp 3209	0.53	0.97	1.64	4.16	3.41	7.57
Arp 4003	0.16	0.34	0.75	3.16	2.26	5.42
Arp 4025	0.28	0.95	1.13	3.52	2.89	6.41
Arp 4329	0.18	0.38	0.76	3.35	2.87	6.21

Table 16: The Molecular Band Indices of the M2+ Giants in the -6° Field

Star	Blanco ^a Bin	MK ^b Bin	I(7100)	I(7450)	I(7890)	S(7890)	I(8197)	I(8460)
6-003	5	7	1.118	-0.050	0.916	1.084	0.034	0.617
6-007	5	7	1.157	-0.019	0.995	1.190	0.031	0.661
6-009	5	5	0.979	-0.073	0.682	0.792	0.034	0.453
6-012	5	5	1.194	-0.035	0.784	0.962	0.098	0.525
6-016	2	2	0.653	-0.041	0.281	0.336	0.032	0.169
6-019	5	5	1.037	-0.073	0.628	0.748	0.029	0.426
6-021	2	2	0.347	-0.001	0.101	0.134	0.048	0.035
6-023	5	7	1.179	-0.047	0.980	1.167	0.003	0.628
6-028	2	2	0.587	-0.020	0.134	0.194	0.041	0.091
6-029	5	2	0.844	-0.057	0.417	0.487	0.045	0.283
6-037	5	2	0.625	-0.039	0.234	0.280	0.054	0.122
6-039	2	2	0.630	-0.036	0.231	0.287	0.024	0.145
6-043	7V	7V	0.958	0.060	0.901	1.146	0.018	0.655
6-044	5	7	1.196	0.029	1.089	1.334	0.072	0.685
6-047	2	2	0.458	-0.018	0.124	0.157	0.031	0.086
6-050	5	2	0.721	-0.046	0.297	0.360	0.035	0.185
6-053	7V	7V	0.689	0.564	1.184	1.637	-0.050	0.851
6-055	2	2	0.317	-0.001	0.085	0.094	0.035	0.023
6-058	5	7	0.659	0.169	0.946	1.270	0.027	0.604
6-060	7	2	0.774	-0.015	0.208	0.262	0.067	0.182
6-067	2	2	0.402	-0.003	0.104	0.110	0.044	0.021
6-069	5	7	1.101	-0.044	0.985	1.171	0.032	0.644
6-074	2	2	0.603	-0.043	0.218	0.269	0.023	0.120
6-075	5	2	0.541	-0.030	0.176	0.211	0.035	0.089
6-080	5	2	0.809	-0.058	0.419	0.496	0.050	0.276
6-082	5	7	1.241	-0.056	0.869	1.032	0.037	0.614
6-088	5	7	1.000	-0.044	0.926	1.121	0.017	0.552
6-091	5	2	0.744	-0.047	0.341	0.428	0.058	0.195
6-093	5	2	0.795	-0.057	0.388	0.500	0.070	0.254
6-095	5	7	0.971	-0.046	0.880	1.055	0.054	0.577
6-099	5	5	1.068	-0.066	0.818	0.975	0.038	0.515
6-109	7	7	1.141	0.005	0.999	1.219	0.077	0.639
6-114	7V	7V	1.406	0.255	1.288	1.654	0.109	0.860
6-124	7	7	1.766	0.109	1.270	1.584	-0.029	0.775
6-137	7	7	1.115	0.201	1.113	1.462	0.008	0.689
6-153	7	7	1.323	0.286	1.186	1.567	-0.004	0.770
6-163	7V	7V	1.068	0.349	1.158	1.558	0.005	0.742
6-169	7	7	1.134	0.125	1.057	1.359	0.060	0.673
6-170	7	7	1.383	0.225	1.257	1.614	0.066	0.813
6-171	7	5	1.071	-0.074	0.619	0.729	0.027	0.435
6-199	7	7	1.111	0.015	1.013	1.239	0.096	0.651
6-212	7	7	1.074	0.229	1.123	1.484	0.058	0.708
6-227	7	7	1.262	0.211	1.168	1.521	0.061	0.738
6-235	7V	7V	1.545	0.740	1.747	2.289	0.025	1.080

^aspectral type bin taken from Frogel *et al.* (1990); 0=K-M1, 2=M2-4, 5=M5-6, 7=M7+^bspectral type bin derived from TiO band strength (see text)

Table 17: The Atomic Line Indices of the M2+ Giants in the -6° Field

Star	Na I	Mg8807	Ca8498	Ca8542	Ca 8662	Ca II
6-003	-2.77	-0.12	-5.19	-1.13	2.79	1.66
6-007	-3.12	-0.06	-7.46	-2.32	3.03	0.71
6-009	-1.53	0.37	-1.99	2.08	3.07	5.15
6-012	0.51	-0.60	-1.82	0.69	2.74	3.43
6-016	-0.22	0.49	0.70	4.09	2.84	6.93
6-019	-1.62	0.25	-1.39	2.25	1.89	4.14
6-021	0.86	0.71	1.62	4.43	4.02	8.45
6-023	-4.18	0.00	-7.67	-1.55	2.52	0.97
6-028	0.58	0.07	1.43	3.43	2.58	6.01
6-029	-0.18	0.30	0.65	3.32	2.94	6.25
6-037	0.53	0.91	0.99	4.17	3.47	7.64
6-039	-0.01	0.66	1.19	4.15	2.76	6.91
6-043	-3.60	-0.06	-4.12	0.20	1.45	1.65
6-044	-2.75	-0.38	-10.10	-3.93	3.30	-0.63
6-047	0.42	0.80	1.58	4.11	3.42	7.53
6-050	0.06	0.77	1.31	4.44	3.41	7.85
6-053	-6.47	0.07	-1.76	-0.66	2.57	1.91
6-055	0.84	0.69	1.78	4.70	3.83	8.53
6-058	-4.30	-0.40	-5.02	-1.77	2.85	1.08
6-060	1.07	0.49	0.52	1.92	0.62	2.54
6-067	1.26	0.92	1.22	3.80	3.65	7.45
6-069	-3.44	-0.14	-7.37	-1.56	2.87	1.31
6-074	-0.26	0.60	0.58	3.65	2.78	6.43
6-075	0.62	1.06	1.61	4.63	2.74	7.37
6-080	-0.09	0.78	0.68	4.07	2.88	6.94
6-082	-2.60	0.09	-3.69	0.70	2.23	2.93
6-088	-3.48	0.00	-6.20	-0.91	2.48	1.56
6-091	0.43	0.61	1.36	4.17	3.35	7.51
6-093	0.53	0.15	1.08	3.59	3.01	6.60
6-095	-2.03	0.24	-4.15	0.45	2.79	3.24
6-099	-2.40	0.17	-3.02	1.36	2.36	3.72
6-109	-1.92	-0.41	-7.07	-2.20	3.44	1.23
6-114	-2.02	-1.12	-11.64	-5.76	3.62	-2.14
6-124	-7.03	-0.21	-12.47	-4.82	3.22	-1.61
6-137	-4.98	-0.19	-6.94	-3.02	2.73	-0.29
6-153	-5.77	-0.22	-6.21	-2.93	2.78	-0.16
6-163	-5.18	-0.33	-4.36	-1.84	2.60	0.76
6-169	-3.42	-0.52	-7.49	-3.56	2.78	-0.78
6-170	-3.83	-0.63	-11.56	-5.07	3.52	-1.55
6-171	-1.63	0.42	-0.95	2.24	2.18	4.41
6-199	-1.20	-0.53	-8.81	-3.20	3.80	0.60
6-212	-3.37	-0.71	-6.92	-3.32	3.15	-0.17
6-227	-3.56	-0.67	-7.88	-3.86	2.93	-0.93
6-235	-4.68	-0.34	-6.84	-3.75	4.45	0.71

Table 18: The Molecular Band Indices of the K-M1 Giants in the -6° Field

Star	Blanco ^a Bin	MK ^b Bin	I(7100)	I(7450)	I(7890)	S(7890)	I(8197)	I(8460)
6-006	2	0	0.187	-0.011	0.030	0.046	0.010	0.007
6-034	2	0	0.211	0.010	0.042	0.053	0.036	0.019
6-058A	...	0	-0.011	0.008	0.005	-0.032	0.005	-0.006
6-061	2	0	0.119	0.001	0.012	0.041	0.024	-0.005
6-083	2	0	0.108	0.003	0.015	0.049	0.024	0.026
6-085	5	0	1.303	0.617	1.338	1.803	-0.056	0.981
6-097	2	0	0.010	0.017	0.022	0.064	0.043	0.007
6-104	2	0	0.158	0.007	0.053	0.095	0.043	-0.006
6-254	C	0	0.074	0.066	-0.015	-0.209	-0.066	-0.023

^aspectral type bin taken from Frogel *et al.* (1990); 0=K-M1, 2=M2-4, 5=M5-6, 7=M7+

^bspectral type bin derived from TiO band strength (see text)

Table 19: The Atomic Line Indices of the K-M1 Giants in the -6° Field

Star	Na I	Mg8807	Ca8498	Ca8542	Ca 8662	Ca II
6-006	0.66	0.57	1.15	4.06	2.92	6.98
6-034	0.69	0.98	1.14	4.18	4.06	8.24
6-058A	0.20	0.36	1.04	3.65	3.41	7.06
6-061	0.08	0.62	1.46	4.06	3.05	7.11
6-083	-0.06	0.66	1.19	4.13	2.73	6.87
6-085	-7.12	-0.18	-2.26	-0.43	3.01	2.58
6-097	0.82	-0.35	1.39	4.01	3.73	7.73
6-104	0.79	0.60	1.44	4.12	3.41	7.53
6-254	-1.38	0.96	-1.09	3.31	1.65	4.96

Table 20: The Molecular Band Indices of the M2+ Giants in the -8° Field

Star	Blanco ^a Bin	MK ^b Bin	I(7100)	I(7450)	I(7890)	S(7890)	I(8197)	I(8460)
8-001	2	2	...	...	...	0.144	0.029	0.081
8-004	7	7	...	...	...	1.412	-0.012	0.692
8-006	5	7	...	...	...	1.328	0.023	0.711
8-007	2	2	...	...	...	0.089	0.045	0.034
8-008	5	2	...	...	...	0.366	0.042	0.202
8-009	5	7	...	...	...	1.099	0.031	0.625
8-012	5	2	...	...	...	0.261	0.024	0.161
8-014	7	7	...	...	...	1.445	0.023	0.691
8-019	5	2	...	...	...	0.498	0.044	0.278
8-025	2	2	...	...	...	0.202	0.039	0.107
8-026	2	2	...	...	...	0.370	0.058	0.234
8-029	7V	7V	1.048	0.024	0.543	0.690	0.030	0.465
8-032	5	5	...	...	...	0.643	0.061	0.412
8-033	7	7	...	...	...	1.428	0.107	0.773
8-034	5V	7V	...	...	...	0.231	0.036	0.289
8-035	2	5	...	...	...	0.699	0.055	0.412
8-038	2	2	...	...	...	0.189	0.037	0.125
8-043	7V	7V	1.192	0.303	1.338	1.755	0.041	0.906
8-044	5	5	...	...	...	0.599	0.068	0.381
8-057	5	2	...	...	...	0.181	0.024	0.097
8-059	5	5	...	...	...	0.935	0.037	0.546
8-077	5	5	...	...	...	0.740	0.046	0.484
8-078	5	5	...	...	...	0.573	0.035	0.333
8-081	7V	7V	...	...	...	1.616	0.045	0.824
8-086	7V	7V	1.341	0.269	1.332	1.708	0.002	0.919
8-088	5	7	1.204	-0.062	0.911	1.071	-0.002	0.612
8-093	7	7	...	...	...	1.170	0.025	0.641
8-096	7V	7V	1.335	0.170	1.148	1.456	0.033	0.802
8-109	5	2	0.583	-0.054	0.208	0.249	0.014	0.121
8-110	2V	7V	0.670	-0.030	0.089	0.110	0.014	0.068
8-116	7	7	...	...	...	1.232	0.054	0.670
8-119	7	7	...	...	...	1.518	0.009	0.701
8-121	5	2	...	...	...	0.334	0.001	0.152
8-123	7	2	...	...	...	0.431	0.021	0.250
8-127	5	2	...	...	...	0.299	0.034	0.145
8-149	2	2	...	...	...	0.165	0.012	0.058

^aspectral type bin taken from Frogel *et al.* (1990); 0=K-M1, 2=M2-4, 5=M5-6, 7=M7+^bspectral type bin derived from TiO band strength (see text)

Table 21: The Atomic Line Indices of the M2+ Giants in the -8° Field

Star	Na I	Mg8807	Ca8498	Ca8542	Ca 8662	Ca II
8-001	-0.28	-0.32	1.62	4.54	2.30	6.83
8-004	-6.88	-0.02	-14.12	-5.35	3.55	-1.80
8-006	-4.99	0.07	-12.41	-4.67	3.07	-1.60
8-007	1.68	-0.35	1.36	4.92	3.23	8.15
8-008	0.62	0.44	1.27	4.28	3.28	7.55
8-009	-3.28	-0.20	-6.92	-1.95	2.53	0.58
8-012	-0.02	0.46	1.36	4.61	2.56	7.17
8-014	-4.78	-0.16	-7.95	-3.04	3.01	-0.03
8-019	0.97	-0.16	0.93	3.69	3.98	7.67
8-025	0.89	0.44	1.93	4.58	3.44	8.01
8-026	1.15	0.50	1.14	4.14	3.03	7.17
8-029	-1.35	0.12	-1.26	0.95	0.72	1.67
8-032	0.44	-0.32	0.25	2.84	2.82	5.66
8-033	-1.41	-1.47	-11.25	-5.11	3.27	-1.84
8-034	-0.30	0.61	0.68	2.70	-0.49	2.22
8-035	-1.20	0.50	-1.05	2.83	2.43	5.26
8-038	0.69	0.53	1.49	4.43	3.41	7.83
8-043	-5.15	-2.24	-7.17	-3.24	3.67	0.43
8-044	0.89	-0.74	1.10	3.19	3.11	6.29
8-057	-0.21	0.76	1.40	4.81	2.22	7.02
8-086	-5.99	-0.23	-9.69	-4.04	3.61	-0.44
8-088	-4.17	0.03	-6.05	-0.73	2.33	1.60
8-093	-3.66	-1.03	-4.24	0.09	1.93	2.01
8-096	-3.91	-0.50	-8.15	-3.24	2.49	-0.75
8-109	-0.49	0.78	1.32	4.76	3.00	7.77
8-110	0.15	0.57	0.64	2.40	1.01	3.41
8-116	-2.08	-0.60	-4.51	-0.49	2.10	1.61
8-119	-4.84	-0.48	-2.61	-1.05	1.70	0.65
8-121	-1.25	-0.54	1.34	5.42	1.67	7.08
8-123	-0.37	-0.74	1.48	4.06	1.54	5.60
8-127	-0.13	-0.68	1.55	4.72	2.29	7.00
8-149	-0.23	-0.54	1.59	4.63	2.36	6.99

Table 22: The Molecular Band Indices of the K-M1 Giants in the -8° Field

Star	Blanco ^a Bin	MK ^b Bin	I(7100)	I(7450)	I(7890)	S(7890)	I(8197)	I(8460)
8-021	2	0	...	...	...	0.045	0.029	0.014
8-054	2	0	...	...	...	-0.024	0.017	-0.003
8-063	2	0	...	...	...	0.016	0.011	0.009
8-106	2	0	0.103	-0.005	0.010	0.009	0.011	-0.005
8-124	2	0	...	...	...	0.022	0.004	0.000
8-137	2	0	...	...	...	0.033	0.012	-0.014
8-153	2	0	...	...	...	0.047	0.016	-0.004

^aspectral type bin taken from Frogel *et al.* (1990); 0=K-M1, 2=M2-4, 5=M5-6, 7=M7+

^bspectral type bin derived from TiO band strength (see text)

Table 23: The Atomic Line Indices of the K-M1 Giants in the -8° Field

Star	Na I	Mg8807	Ca8498	Ca8542	Ca 8662	Ca II
8-021	0.56	1.08	1.34	4.55	3.35	7.90
8-054	0.45	0.06	1.05	4.04	2.38	6.42
8-063	0.09	0.21	1.60	4.97	3.09	8.06
8-106	0.18	0.71	1.33	4.23	3.10	7.32
8-124	-0.57	-0.45	1.43	3.89	2.41	6.30
8-137	0.43	-0.37	1.69	4.23	3.46	7.69
8-153	0.74	-0.07	2.45	5.18	3.08	8.26

Table 24: The Molecular Band Indices of the M2+ Field Giants

Star	MK ^a Type	TiO ^b Type	I(7100)	I(7450)	I(7890)	S(7890)	I(8197)	I(8460)
HD 79669	M5	M5	...	...	...	0.670	0.046	0.411
HD 82850	M6	M6	...	...	...	0.738	0.050	0.444
HD 85008	M7	M6	...	...	...	0.865	0.045	0.531
HD 89060	M4	M4	0.767	-0.077	0.396	0.428	0.023	0.250
HD 89951	M3	M3	0.781	-0.061	0.321	0.346	0.033	0.208
HD 94152	M6	M7	1.163	-0.066	0.933	1.079	-0.002	0.625
HD 99094	M5	M5	0.949	-0.086	0.567	0.628	0.036	0.366
HD 99495	M4	M4	...	...	...	0.492	0.009	0.299
HD 100569	M2	M2	0.408	-0.031	0.129	0.126	0.021	0.062
HD 102506	M6	M6	...	...	...	0.765	0.051	0.451
HD 102608	M7	M7	1.123	-0.024	1.053	1.247	-0.010	0.653
HD 102766	M3	M7	1.156	-0.044	0.986	1.159	0.002	0.659
HD 106611	K5.5	M2	0.385	-0.022	0.110	0.107	0.019	0.049
HD 109225	M5	M6	1.207	-0.060	0.718	0.828	0.034	0.508
HD 109467	M6	M5	0.963	-0.086	0.577	0.640	0.020	0.387
BK Vir	M7	M7	...	...	...	1.338	-0.013	0.719
RT Vir	M8	M7	...	...	...	1.523	-0.040	0.749
SW Vir	M7	M7	...	...	...	1.523	0.005	0.803

^aspectral type taken from SIMBAD^bspectral type derived from TiO band strength (see text)

Table 25: The Atomic Line Indices of the M2+ Field Giants

Star	Na I	Mg8807	Ca8498	Ca8542	Ca 8662	Ca II
HD 79669	-1.27	0.58	-0.09	3.76	2.16	5.93
HD 82850	-1.45	0.57	-0.09	3.53	2.19	5.72
HD 85008	-2.14	0.42	-1.60	2.11	1.95	4.06
HD 89060	-1.00	0.30	1.09	4.48	2.56	7.04
HD 89951	-0.35	0.53	1.76	4.89	2.64	7.53
HD 94152	-3.96	0.24	-3.97	1.01	1.95	2.96
HD 99094	-1.02	0.35	-0.05	3.28	2.36	5.63
HD 99495	-2.13	0.39	0.56	4.08	2.06	6.14
HD 100569	-0.20	0.48	1.45	4.70	2.78	7.48
HD 102506	-1.65	0.50	-0.63	2.80	2.24	5.04
HD 102608	-5.09	0.00	-7.65	-1.36	2.71	1.34
HD 102766	-3.12	-0.04	-7.60	-1.36	2.68	1.32
HD 106611	0.22	0.61	1.67	4.94	3.34	8.28
HD 109225	-1.40	0.18	-0.04	2.94	2.33	5.26
HD 109467	-1.78	0.49	-0.10	3.55	2.04	5.59
BK Vir	-6.38	0.25	-7.31	-1.77	2.23	0.46
RT Vir	-7.75	-0.01	-8.09	-3.09	2.46	-0.64
SW Vir	-6.64	0.22	-9.53	-3.33	3.01	-0.31

Table 26: The Molecular Band Indices of the K-M1 Field Giants

Star	MK ^a Type	TiO ^b Bin	I(7100)	I(7450)	I(7890)	S(7890)	I(8197)	I(8460)
HD 76409	K0	0	...	...	...	-0.057	0.020	0.006
HD 77567	K1	0	...	...	...	-0.124	0.004	0.020
HD 80108	K4	0	...	...	...	-0.024	0.040	-0.001
HD 81200	K3	0	...	...	...	-0.016	0.036	0.011
HD 84837	K1	0	-0.006	0.002	0.001	-0.072	-0.004	0.016
HD 85825	K4	0	...	...	...	-0.014	0.020	0.009
HD 96722	K1	0	-0.002	-0.004	-0.005	-0.040	0.016	-0.008
HD 97291	K5	0	0.156	-0.006	0.031	0.005	0.026	0.006
HD 100222	K3	0	0.019	-0.004	-0.005	-0.036	0.017	-0.005
HD 100670	K1	0	...	...	...	-0.037	0.005	-0.001
HD 100783	M2	0	0.332	-0.023	0.092	0.088	0.010	0.022
HD 100892	K4	0	0.186	-0.007	0.039	0.022	0.012	0.004
HD 100937	K0	0	-0.013	-0.013	-0.002	-0.043	0.020	0.001
HD 101095	K5	0	0.170	-0.015	0.030	0.024	0.028	0.010
HD 101358	M0	0	0.169	-0.011	0.029	0.016	0.028	0.011
HD 102019	K2	0	-0.005	-0.002	-0.010	-0.045	0.024	0.000
HD 103563	K3	0	0.060	-0.001	0.011	-0.012	0.008	-0.008
HD 107296	M1	0	0.327	-0.015	0.072	0.067	0.026	0.033
HD 110504	K4	0	0.042	-0.001	0.001	-0.043	0.026	-0.003
HD 120223	G8	0	0.002	0.003	-0.005	-0.050	0.018	-0.011

^aspectral type taken from SIMBAD^bspectral type bin derived from TiO band strength (see text)

Table 27: The Atomic Line Indices of the K-M1 Field Giants

Star	Na I	Mg8807	Ca8498	Ca8542	Ca 8662	Ca II
HD 76409	0.27	0.87	1.28	3.84	2.27	6.11
HD 77567	0.10	-1.03	0.77	1.41	1.26	2.67
HD 80108	0.45	0.98	1.91	6.06	4.16	10.22
HD 81200	0.46	0.85	1.47	4.84	2.88	7.72
HD 84837	-0.30	0.03	0.61	1.04	0.37	1.41
HD 85825	0.46	0.86	1.68	4.90	3.57	8.47
HD 96722	0.30	0.51	1.46	3.80	2.68	6.48
HD 97291	0.44	0.81	1.56	4.88	3.15	8.03
HD 100222	0.18	0.72	1.48	4.46	3.01	7.47
HD 100670	-0.30	0.64	1.37	3.82	2.73	6.56
HD 100783	-0.29	0.45	1.49	5.06	2.77	7.83
HD 100892	0.08	0.47	1.46	4.47	3.05	7.52
HD 100937	0.35	0.31	1.26	3.75	2.69	6.45
HD 101095	0.09	0.53	1.52	4.84	3.15	7.98
HD 101358	0.08	0.51	1.58	5.00	3.25	8.25
HD 102019	0.15	0.56	1.22	4.32	3.15	7.47
HD 103563	-0.15	0.28	1.34	4.50	3.13	7.62
HD 107296	0.44	0.74	1.97	5.10	3.36	8.46
HD 110504	0.59	0.71	1.62	4.46	2.82	7.29
HD 120223	0.31	0.48	0.70	3.11	2.31	5.42

Table 28: The Molecular Band Indices of the Field Dwarfs

Star	Blanco ^a Bin	MK ^b Bin	I(7100)	I(7450)	I(7890)	S(7890)	I(8197)	I(8460)
3-040	2	0	0.000	0.005	-0.010	-0.051	0.018	0.019
3-074	2	0	0.005	0.007	-0.001	-0.056	0.023	0.003
3-106	2	0	-0.010	0.000	-0.013	-0.062	0.019	0.001
10-020	5	0	0.156	-0.002	0.055	0.070	0.045	0.022
10-021	2	0	0.003	0.008	-0.010	-0.033	0.040	-0.001
10-029	5	2	...	...	...	0.374	0.109	0.155
10-039	5	2	...	...	...	0.210	0.093	0.055
10-044	5	2	0.214	-0.020	0.084	0.106	0.064	0.039
10-054	7	5	0.682	-0.030	0.460	0.561	0.102	0.300
10-107	5	2	0.387	-0.042	0.195	0.241	0.102	0.104
12-030	2	0	0.025	-0.004	-0.019	-0.014	0.014	-0.012
12-037	2	0	0.004	0.002	0.002	-0.056	-0.017	0.006
12-039	2	0	0.013	0.000	0.006	-0.014	0.028	-0.003
12-047	2	2	0.604	-0.046	0.448	0.533	0.088	0.249
12-051	5	2	0.307	-0.016	0.146	0.182	0.072	0.069
12-057	7	0	-0.002	0.003	-0.004	-0.067	-0.005	0.011
12-061	5	2	0.634	-0.035	0.444	0.538	0.103	0.242
12-071	5	5	0.763	-0.019	0.591	0.717	0.102	0.366
Wolf 359	5	5	...	...	...	0.884	0.292	0.474

^aspectral type bin taken from Frogel *et al.* (1990); 0=K-M1, 2=M2-4, 5=M5-6, 7=M7+^bspectral type bin derived from TiO band strength (see text)

Table 29: The Atomic Line Indices of the Field Dwarfs

Star	Na I	Mg8807	Ca8498	Ca8542	Ca 8662	Ca II
3-040	0.03	0.07	1.16	2.47	2.14	4.60
3-074	0.36	-0.56	1.58	2.98	2.93	5.91
3-106	0.22	0.34	0.70	2.61	1.99	4.61
10-020	1.59	0.74	1.07	2.28	1.02	3.30
10-021	1.22	0.63	0.83	3.33	3.02	6.35
10-029	2.82	0.33	0.65	2.03	0.19	2.22
10-039	2.74	0.63	0.51	1.88	-0.24	1.64
10-044	2.09	0.87	0.73	2.16	1.32	3.48
10-054	2.29	0.28	0.90	2.12	-0.25	1.87
10-107	2.88	0.37	0.94	2.38	0.79	3.16
12-030	0.23	0.33	1.28	3.73	2.45	6.17
12-037	-0.15	0.47	0.94	2.92	2.00	4.92
12-039	1.20	0.77	1.27	3.07	1.84	4.91
12-047	1.92	-0.65	-0.03	1.14	0.57	1.71
12-051	2.69	-0.41	0.97	2.42	2.95	5.37
12-057	0.46	0.34	0.78	2.99	2.10	5.09
12-061	2.48	-0.07	0.99	2.59	0.53	3.12
12-071	2.18	-0.30	-0.03	2.08	0.54	2.62
Wolf 359	5.68	0.84	2.74	3.72	-1.09	2.63

Table 30: The Definitions of the Baade's Window Models

Model	Color-Magnitude Data ^a		Luminosity Function ^b	
	$I_0 < 15.25$	$I_0 > 15.25$	$I_0 < 15.25$	$I_0 > 15.25$
C	CMD	T88 + VB	CMD	Worthey
c	CMD	T88 + VB	CMD	TFW
W	T88	T88 + VB	Worthey	Worthey
w	T88	T88 + VB	CMD	Worthey
T	T88	T88 + VB	TFW	TFW
t	T88	T88 + VB	CMD	TFW

^aCMD = photometry from Figure 24

T88 = revised and shifted Terndrup (1988) ridge line (see text)

VB = 8.0 Gyr, Z=0.0100 VandenBerg (1985) isochrone

^bCMD = photometry from Figure 24

Worthey = Worthey (1994)

TFW = Terndrup *et al.* (1990)

Table 31: The Integrated Photometry of the Baade's Window Models

Component	$(V - I)_0$	$(V - K)_0$	$(J - K)_0$	$(H - K)_0$	CO	H ₂ O
Model C: Basic Baade's Window Model						
dwarfs	0.847	2.065	0.543	0.102	0.020	0.064
subgiants	0.773	1.859	0.447	0.065	0.042	0.031
giants	1.395	3.583	0.843	0.168	0.208	0.086
total	1.158	3.078	0.778	0.154	0.170	0.081
Model c						
dwarfs	0.786	1.890	0.495	0.082	0.024	0.047
subgiants	0.775	1.867	0.448	0.064	0.043	0.031
giants	1.369	3.530	0.835	0.165	0.205	0.085
total	1.154	3.084	0.779	0.153	0.178	0.079
Model w						
dwarfs	0.847	2.065	0.543	0.102	0.020	0.064
subgiants	0.773	1.859	0.447	0.065	0.042	0.031
giants	1.437	3.540	0.828	0.172	0.201	0.049
total	1.175	3.022	0.761	0.157	0.162	0.052
Model W						
dwarfs	0.847	2.065	0.543	0.102	0.020	0.064
subgiants	0.773	1.859	0.447	0.065	0.042	0.031
giants	1.441	3.599	0.846	0.176	0.205	0.053
total	1.179	3.073	0.778	0.160	0.167	0.054
Model t						
dwarfs	0.786	1.890	0.495	0.082	0.024	0.047
subgiants	0.775	1.867	0.448	0.064	0.043	0.031
giants	1.407	3.484	0.820	0.169	0.199	0.049
total	1.172	3.026	0.761	0.155	0.169	0.048
Model T						
dwarfs	0.786	1.890	0.495	0.082	0.024	0.047
subgiants	0.775	1.867	0.448	0.064	0.043	0.031
giants	1.437	3.604	0.844	0.170	0.206	0.054
total	1.208	3.161	0.791	0.158	0.180	0.053

Table 32: The Integrated Molecular Band Indices of the Baade's Window Models

Component	I(7100)	I(7450)	I(7890)	S(7890)	I(8197)	I(8460)
Model C: Basic Baade's Window Model						
dwarfs	0.011	-0.001	0.003	0.004	0.020	0.001
subgiants	0.000	0.000	0.000	0.000	0.010	0.000
giants	0.203	-0.011	0.102	0.128	0.018	0.068
total	0.128	-0.007	0.064	0.081	0.019	0.043
Model c						
dwarfs	0.004	0.000	0.001	0.001	0.017	0.000
subgiants	0.000	0.000	0.000	0.000	0.010	0.000
giants	0.192	-0.011	0.096	0.121	0.018	0.065
total	0.131	-0.008	0.066	0.083	0.018	0.044
Model w						
dwarfs	0.011	-0.001	0.003	0.004	0.020	0.001
subgiants	0.000	0.000	0.000	0.000	0.010	0.000
giants	0.231	-0.018	0.110	0.139	0.021	0.072
total	0.143	-0.012	0.068	0.086	0.020	0.045
Model W						
dwarfs	0.011	-0.001	0.003	0.004	0.020	0.001
subgiants	0.000	0.000	0.000	0.000	0.010	0.000
giants	0.235	-0.020	0.122	0.151	0.021	0.081
total	0.147	-0.013	0.076	0.094	0.020	0.051
Model t						
dwarfs	0.004	0.000	0.001	0.001	0.017	0.000
subgiants	0.000	0.000	0.000	0.000	0.010	0.000
giants	0.218	-0.017	0.104	0.131	0.021	0.068
total	0.146	-0.012	0.070	0.089	0.020	0.047
Model T						
dwarfs	0.004	0.000	0.001	0.001	0.017	0.000
subgiants	0.000	0.000	0.000	0.000	0.010	0.000
giants	0.239	-0.020	0.126	0.155	0.021	0.084
total	0.167	-0.014	0.088	0.109	0.020	0.059

Table 33: The Integrated Atomic Line Indices of the Baade's Window Models

Component	Na I	Mg8807	Ca8498	Ca8542	Ca 8662	Ca II
Model C: Basic Baade's Window Model						
dwarfs	0.48	0.50	0.95	2.91	1.99	4.90
subgiants	0.21	0.38	0.92	3.03	2.43	5.46
giants	0.03	0.53	0.72	3.56	3.07	6.63
total	0.19	0.52	0.81	3.32	2.69	6.01
Model c						
dwarfs	0.39	0.49	0.95	2.94	2.06	5.00
subgiants	0.21	0.38	0.92	3.03	2.43	5.47
giants	0.04	0.52	0.74	3.55	3.07	6.62
total	0.14	0.51	0.81	3.37	2.76	6.13
Model w						
dwarfs	0.48	0.50	0.95	2.91	1.99	4.90
subgiants	0.21	0.38	0.92	3.03	2.43	5.46
giants	0.18	0.55	1.02	3.78	3.05	6.83
total	0.28	0.53	0.99	3.46	2.67	6.12
Model W						
dwarfs	0.48	0.50	0.95	2.91	1.99	4.90
subgiants	0.21	0.38	0.92	3.03	2.43	5.46
giants	0.10	0.53	0.86	3.67	3.03	6.70
total	0.23	0.52	0.89	3.39	2.66	6.05
Model t						
dwarfs	0.39	0.49	0.95	2.94	2.06	5.00
subgiants	0.21	0.38	0.92	3.03	2.43	5.47
giants	0.18	0.54	1.02	3.76	3.04	6.81
total	0.24	0.52	1.00	3.51	2.74	6.25
Model T						
dwarfs	0.39	0.49	0.95	2.94	2.06	5.00
subgiants	0.21	0.38	0.92	3.03	2.43	5.47
giants	0.07	0.52	0.80	3.62	3.02	6.64
total	0.16	0.51	0.85	3.43	2.75	6.18

Table 34: The Average Offsets from the Baade's Window Calibration Relations

		Sgr I Field	Baade's Window	-6° Field	-8° Field	Field Giants	Field Dwarfs
$\delta(J-H)_o$	median	0.010	-0.001	0.017	0.013	0.068	...
	mean	0.011	-0.004	0.013	0.016	0.070	...
	n	27	144	35	59	18	...
δCO	median	0.002	-0.002	-0.003	-0.012	-0.038	...
	mean	0.002	-0.004	-0.006	-0.017	-0.040	...
	n	30	140	44	73	15	...
$\delta(H-K)_{H_2O}$	median	-0.003	-0.000	-0.021	-0.007	-0.021	...
	mean	-0.009	0.003	-0.023	-0.011	-0.020	...
	n	22	61	31	33	4	...
$\delta(H-K)_{I(7100)}$	median	0.010	-0.007	-0.001	0.001	0.022	0.099
	mean	0.013	-0.004	-0.001	0.001	0.022	0.101
	n	21	8	29	1	6	6
$\delta(H-K)_{I(7890)}$	median	-0.000	-0.002	-0.007	-0.005	0.025	0.080
	mean	0.003	-0.000	-0.005	-0.005	0.021	0.079
	n	19	9	30	2	7	6
$\delta(H-K)_{S(7890)}$	median	-0.001	-0.001	-0.008	0.007	0.032	0.083
	mean	0.002	0.001	-0.004	0.009	0.031	0.080
	n	23	26	30	27	9	9
$\delta(H-K)_{I(8460)}$	median	0.000	-0.001	-0.010	0.001	0.021	0.087
	mean	0.003	-0.003	-0.006	0.003	0.020	0.087
	n	19	22	27	24	6	7

Table 35: The Integrated Photometry of the Galactic Bulge Models

Component	$(V - I)_0$	$(V - K)_0$	$(J - K)_0$	$(H - K)_0$	CO	H ₂ O
Z=0.0092, $\tau=8.0$ Gyr -6° Model						
dwarfs	0.838	2.046	0.539	0.101	0.020	0.063
subgiants	0.794	1.887	0.441	0.055	0.046	0.031
giants	1.430	3.534	0.827	0.173	0.201	0.049
total	1.158	2.993	0.756	0.156	0.160	0.052
Z=0.0100, $\tau=7.0$ Gyr -6° Model						
dwarfs	0.835	2.043	0.540	0.101	0.020	0.063
subgiants	0.777	1.848	0.440	0.061	0.042	0.031
giants	1.435	3.544	0.828	0.173	0.202	0.049
total	1.154	2.987	0.756	0.156	0.160	0.052
Z=0.0084, $\tau=8.0$ Gyr -8° Model						
dwarfs	0.827	2.024	0.535	0.099	0.020	0.062
subgiants	0.783	1.870	0.448	0.057	0.043	0.031
giants	1.322	3.237	0.773	0.146	0.182	0.040
total	1.099	2.785	0.707	0.133	0.141	0.045
Z=0.0100, $\tau=6.0$ Gyr -8° Model						
dwarfs	0.812	1.990	0.527	0.098	0.020	0.062
subgiants	0.769	1.828	0.437	0.057	0.040	0.030
giants	1.326	3.246	0.774	0.147	0.183	0.040
total	1.091	2.771	0.708	0.134	0.140	0.045

Table 36: The Integrated Molecular Band Indices of the Galactic Bulge Models

Component	I(7100)	I(7450)	I(7890)	S(7890)	I(8197)	I(8460)
Z=0.0092, $\tau=8.0$ Gyr -6° Model						
dwarfs	0.011	-0.001	0.003	0.004	0.020	0.001
subgiants	0.000	0.000	0.000	0.000	0.010	0.000
giants	0.232	-0.019	0.112	0.141	0.021	0.074
total	0.140	-0.012	0.068	0.085	0.020	0.045
Z=0.0100, $\tau=7.0$ Gyr -6° Model						
dwarfs	0.011	-0.001	0.003	0.004	0.020	0.001
subgiants	0.000	0.000	0.000	0.000	0.010	0.000
giants	0.235	-0.019	0.113	0.142	0.021	0.074
total	0.141	-0.012	0.068	0.085	0.020	0.045
Z=0.0084, $\tau=8.0$ Gyr -8° Model						
dwarfs	0.011	-0.001	0.002	0.004	0.019	0.001
subgiants	0.000	0.000	0.000	0.000	0.010	0.000
giants	0.170	-0.012	0.065	0.087	0.019	0.041
total	0.104	-0.008	0.040	0.054	0.019	0.025
Z=0.0100, $\tau=6.0$ Gyr -8° Model						
dwarfs	0.010	-0.001	0.002	0.004	0.019	0.001
subgiants	0.000	0.000	0.000	0.000	0.010	0.000
giants	0.172	-0.013	0.065	0.088	0.019	0.042
total	0.105	-0.008	0.040	0.054	0.019	0.025

Table 37: The Integrated Atomic Line Indices of the Galactic Bulge Models

Component	Na I	Mg8807	Ca8498	Ca8542	Ca 8662	Ca II
Z=0.0092, $\tau=8.0$ Gyr -6° Model						
dwarfs	0.47	0.50	0.95	2.91	2.00	4.91
subgiants	0.22	0.38	0.93	3.05	2.44	5.49
giants	0.17	0.54	1.00	3.76	3.03	6.79
total	0.28	0.52	0.98	3.43	2.65	6.08
Z=0.0100, $\tau=7.0$ Gyr -6° Model						
dwarfs	0.47	0.50	0.95	2.91	2.00	4.91
subgiants	0.21	0.38	0.93	3.03	2.42	5.45
giants	0.17	0.54	1.00	3.76	3.03	6.79
total	0.28	0.52	0.98	3.43	2.64	6.07
Z=0.0084, $\tau=8.0$ Gyr -8° Model						
dwarfs	0.46	0.50	0.95	2.91	2.01	4.92
subgiants	0.21	0.38	0.92	3.04	2.43	5.47
giants	0.32	0.55	1.31	3.92	3.06	6.98
total	0.37	0.53	1.17	3.53	2.67	6.20
Z=0.0100, $\tau=6.0$ Gyr -8° Model						
dwarfs	0.45	0.50	0.95	2.92	2.02	4.93
subgiants	0.20	0.38	0.92	3.03	2.42	5.44
giants	0.32	0.56	1.31	3.92	3.06	6.99
total	0.37	0.53	1.17	3.53	2.66	6.18

Figure 23: The relationship between MK spectral type and TiO band strength for field giants. (a) MK spectral type *vs.* the TiO index $S(7890)$; (b) MK spectral type *vs.* the TiO index $I(8460)$. The MK spectral types are taken from the SIMBAD database and usually come from Volumes I-III of the Michigan Spectral Catalogue (Houk 1978, Houk 1982, Houk & Smith-Moore 1988); the TiO band strengths and spectral types are those given in Table 24. The solid curve is a second-order least-squares fit to the stars having MK types later than M0 (excluding the point enclosed in parentheses) and has been used to predict MK spectral types for the Galactic bulge stars. The vertical dotted lines show the predicted TiO band strengths for MK spectral types M1.5, M4.5 and M6.5. Crosses and filled circles represent stars having average spectral types earlier than M2 and M2 or later, respectively, based upon their $S(7890)$ and $I(8460)$ indices. The asterisk represents the dwarf star Wolf 359.

Figure 24: The I_0 , $(V - I)_0$ color-magnitude diagram for a region surrounding the globular cluster NGC 6522 in Baade's Window (Terndrup 1994; private communication). The stars shown all lie more than $2.5'$ from the cluster center in a region having a total area of 39.7 arcmin^2 . The revised and shifted giant branch ridge line taken from Terndrup (1988) overlays the data; see the text for a further explanation of this ridge line. The arrow represents the reddening and extinction correction which has been applied to the data. The solid box encloses the stars included in the basic Baade's Window model described in the text.

Figure 25: Gaussian fits to the color distribution of the stars in the Baade's Window (BW) color-magnitude diagram (Figure 24). Each panel represents the stars in a 0.25 mag. bin in I_0 ; the illustrated bins have central magnitudes of: (a) $I_0 = 13.125$, (b) $I_0 = 13.375$, (c) $I_0 = 13.625$, (d) $I_0 = 13.875$, (e) $I_0 = 14.125$, (f) $I_0 = 14.375$, (g) $I_0 = 14.625$. The histogram in each panel gives the number of stars per 0.1 mag. bin in $(V - I)_0$. The light, solid curves represent Gaussian fits to the BW stars; the dotted curves are Gaussian fits to the disk main-sequence stars, BW clump stars (for $I_0 = 14.375$) or other stars contaminating the color-magnitude diagram. The heavy, solid curves are the sums of the individual Gaussian fits.

Figure 26: Gaussian fits to the color distribution of the stars in the Baade's Window (BW) color-magnitude diagram (Figure 24). Each panel represents the stars in a 0.25 mag. bin in I_0 ; the illustrated bins have central magnitudes of: (a) $I_0 = 14.875$, (b) $I_0 = 15.125$, (c) $I_0 = 15.375$, (d) $I_0 = 15.625$, (e) $I_0 = 15.875$, (f) $I_0 = 16.125$, and (g) $I_0 = 17.625$. The histogram in each panel gives the number of stars per 0.1 mag. bin in $(V - I)_0$. The light, solid curves represent Gaussian fits to the BW stars; the dotted curves are Gaussian fits to the disk main-sequence stars, BW clump stars (for $I_0 = 14.375$) or other stars contaminating the color-magnitude diagram. The heavy, solid curves are the sums of the individual Gaussian fits.

Figure 27: Characteristics of the distribution of stars in the Baade's Window color-magnitude diagram. The solid lines represent linear least-squares fits to the solid points and are the initial relations used to extrapolate the parameters to fainter magnitudes. The circles represent data provided directly from the Gaussian fits shown in Figures 25 and 26 and described in the text. a) the average color of the disk star main sequence as a function of magnitude. b) the FWHM of the disk star color distribution as a function of magnitude; the solid line represents $\text{FWHM} = 0.26$. c) the number of disk stars as a function of magnitude; the triangles represent the number of stars bluer than $(V-I)_0 = 0.85$. d) the total number of stars in the Baade's Window color-magnitude diagram as a function of magnitude.

Figure 28: Gaussian fits to the color distribution of the stars remaining in the Baade's Window (BW) color-magnitude diagram after the initial removal of the disk stars along the line of sight to BW. Each panel represents the stars in a 0.25 mag. in I_0 ; the illustrated bins have central magnitudes of: (a) $I_0 = 15.875$, (b) $I_0 = 16.125$, (c) $I_0 = 16.375$, (d) $I_0 = 16.625$, (e) $I_0 = 16.875$, (f) $I_0 = 17.125$, (g) $I_0 = 17.375$, and (h) $I_0 = 17.625$. The histogram in each panel gives the number of stars per 0.1 mag. bin in $(V-I)_0$. The solid curves represent Gaussian fits to the color histograms.

Figure 29: Comparison of the color-magnitude sequence of the Baade's Window (BW) stars to Vandenberg (1985) isochrones. The open dots are the average colors of the BW stars in the original CMD; the solid dots represent the average color of the BW stars after removal of the disk contamination. Horizontal error bars show the range in color which results from varying *all* of the disk star extrapolations as discussed in the text. The vertical error bar on the point at $I_0 = 17.125$ shows the magnitude variation caused by a ± 1.0 kpc change in R_0 . Moving from blue to red in each panel, the isochrones shown have: a) $Z = 0.0169$ and $\tau = 5, 6, 8, 10, 12.5$ and 15 Gyr; b) $Z = 0.0100$ and $\tau = 3, 4, 5, 6, 8, 10, 12.5$ and 15 Gyr; c) $\tau = 8$ Gyr and $Z = 0.0060, 0.0100$ and 0.0169 ; and d) $\tau = 15$ Gyr and $Z = 0.0100$ and 0.0169 .

Figure 30: The Cousins I -band luminosity functions (LFs) used in the Baade's Window (BW) models. The solid dots represent the LF derived here, which consists of three sections - for $I_0 < 15.25$, it is the number of stars having $(V - I)_0 \geq 0.85$ in the BW color-magnitude diagram shown in Figure 24; star counts for the bins centered at $I_0 = 15.375$ and $I_0 = 15.625$ are the number of stars enclosed in the Gaussians fit to the color-magnitude diagram before the disk star contamination was removed (see Figure 26); the star counts for fainter magnitudes come from the analogous Gaussian fits after disk star removal (see Figure 28). The histogram is the LF estimated from Figure 12 of Terndrup *et al.* (1990) and has been adjusted to the I -band extinction assumed here. The open dots are a theoretical LF from the $Z = 0.0100$, $Y = 0.255$, $\tau = 8.0$ Gyr stellar population model of Worthey (1994) and have been adjusted to $R_0 = 8.0$ kpc.

Figure 31: The Baade's Window (BW) calibration relation between $(V - I)_0$ and $(H - K)_0$. The BW giants not known to be variable are shown as filled circles if their MK spectral types are M2 or later and as crosses if they have MK spectral types earlier than M2. The BW variables are shown as open circles if classified as Mira variables by Lloyd-Evans (1976); open squares are stars not known to be Miras but having I magnitudes which were observed to vary by more than 0.3 mag. by Blanco *et al.* (1984). The dashed lines represent the colors of Bessell *et al.* (1989) models of $1 M_{\odot}$, solar metallicity Mira variables; the upper and lower lines represent the Miras at minimum and maximum light, respectively, while the effective temperatures of the models range from 3000 - 3500 K in moving from red to blue along each dashed line. The heavy, solid line is the calibration relation derived as described in the text, excluding the variables and the points enclosed within parentheses. The light, solid line is the field giant relation, and the dotted line is the field dwarf trend, both taken from Bessell & Brett (1988). The vector shows the reddening correction applied to the data.

Figure 32: The Baade's Window (BW) calibration relation between $(H-K)_0$ and $(I-K)_0$. All symbols and lines have the same meaning as in Figure 31.

Figure 33: The Baade's Window (BW) calibration relation between $(H - K)_0$ and $(J - H)_0$. The Sgr I and BW giants with MK spectral types later than M2 which are not known to be variable are shown as open and filled circles, respectively; the Sgr I and BW stars having MK spectral types earlier than M2 are shown as crosses. The Sgr I giants designated as LPVs by Frogel *et al.* (1990), the BW giants classified as Mira variables by Lloyd-Evans (1976), and the BW stars having I magnitudes which were observed to vary by more than 0.3 mag. by Blanco *et al.* (1984) are shown as asterisks. The heavy, solid curve is the calibration relation derived as described in the text. The light, solid line is the field giant relation, and the dotted line is the field dwarf trend, both taken from Frogel *et al.* (1978). The vector shows the reddening correction applied to the data.

Figure 34: The Baade's Window (BW) calibration relation between $(H-K)_0$ and CO. All symbols and lines have the same meaning as in Figure 33.

Figure 35: The Baade's Window (BW) calibration relation between $(H-K)_0$ and H_2O . All symbols and lines have the same meaning as in Figure 33.

Figure 36: The Baade's Window (BW) calibration relations between $(H-K)_0$ and the molecular band indices: (a) $I(7100)$, (b) $I(7450)$, (c) $I(7890)$, (d) $S(7890)$, (e) $I(8197)$, and (f) $I(8460)$. All symbols and lines have the same meaning as in Figure 33.

Figure 37: The field star relations between $(H-K)_0$ and the molecular band indices: (a) $I(7100)$, (b) $I(7450)$, (c) $I(7890)$, (d) $S(7890)$, (e) $I(8197)$, and (f) $I(8460)$. Crosses represent field giants with MK spectral types earlier than M2, filled pentagons are field giants with MK spectral types M2 and later, and open pentagons are field dwarfs. The heavy, solid curves are the Baade's Window (BW) calibration relations shown in Figure 36. The light, solid curves are the apparent field giant trends and are simply the BW calibration relations shifted redward by 0.02 mag. in $(H-K)_0$. The dotted curves are the field dwarf relations - in panels (a), (c), (d) and (f), these curves are the BW calibration relations shifted redward by 0.09 mag. in $(H-K)_0$; in panels (b) and (e), they are linear least-squares fits to the dwarf star data (see text).

Figure 38: The Baade's Window (BW) calibration relations between $(H-K)_0$ and the atomic line indices: (a) Na I, (b) Mg8807, (c) Ca8498, (d) Ca8542, (e) Ca8662, and (f) Ca II. Only line widths measured from low-resolution spectra are plotted; otherwise, all symbols and lines have the same meaning as in Figure 33.

Figure 39: The field giant relations between $(H - K)_0$ and the atomic line indices: (a) Na I, (b) Mg 8807, (c) Ca 8498, (d) Ca 8542, (e) Ca 8662, and (f) Ca II. Only line widths measured from low-resolution spectra are plotted; otherwise, all symbols and lines have the same meaning as in Figure 37.

Figure 40: The field dwarf relations between $(H - K)_0$ and the atomic line indices: (a) Na I, (b) Mg8807, (c) Ca8498, (d) Ca8542, (e) Ca8662, and (f) Ca II. Only line widths measured from low-resolution spectra are plotted. Solid lines are the field dwarf relations derived as described in the text.

Figure 41: The color-magnitude sequence used in the Baade's Window (BW) models. The solid curve is a merger of the $Z = 0.0100$, $\tau = 8.0$ Gyr Vandenberg (1985) isochrone and the revised and shifted Terndrup (1988) giant branch ridge line described in the text. The solid circles represent the color-magnitude points input into the BW models. The dashed line shows the lower magnitude cut-off of the photometry (see Figure 24) used in models C (the basic BW model) and c; the entire color-magnitude sequence is used for models W, w, T and t. The dotted box defines the color-magnitude regime in which the subgiants have been assumed to lie.

Figure 42: The photometry of the Baade's Window (BW) models as a function of $(V-K)_0$. Circles represent Virgo elliptical galaxies, and triangles are Virgo lenticulars. The heavy solid lines are linear least-squares fits to the Virgo galaxy data (see Chapter 3); the dotted lines are the 99% confidence limits on the values of the dependent variable predicted by these relations. Open symbols are the galaxies NGC 4382 and NGC 4435, which have been excluded from the sample used to define the linear relations. The BW model results are represented by the symbols C, c, W, w, T and t; see Table 30 for a description of each model. The symbols E and M show the photometry of an average, bright elliptical galaxy and of the BW model, respectively, reported by Terndrup *et al.* (1990).

Figure 43: The photometry of the Baade's Window models as a function of $(J-K)_0$. All symbols and lines have the same meaning as in Figure 42.

Figure 44: The molecular band indices of the Baade's Window models as a function of $(V-K)_0$. All symbols and lines have the same meaning as in Figure 42.

Figure 45: The molecular band indices of the Baade's Window models as a function of $(J-K)_0$. All symbols and lines have the same meaning as in Figure 42.

Figure 46: The atomic line indices of the Baade's Window models as a function of $(V-K)_0$. All symbols and lines have the same meaning as in Figure 42.

Figure 47: The atomic line indices of the Baade's Window models as a function of $(J-K)_0$. All symbols and lines have the same meaning as in Figure 42.

Figure 48: Color-magnitude sequences used to model the Galactic bulge fields at $b = -6^\circ$ and $b = -8^\circ$. (a) from blue to red, the ridge lines used in the models of the -8° field, the -6° field and BW are shown, assuming that a radial metallicity gradient exists in the Galactic bulge; (b) same as (a), but assuming that a radial age gradient exists in the Galactic bulge; (c) the ridge line used in the model of the -6° field, assuming that a radial metallicity gradient exists in the Galactic bulge; all lines have the same meaning as in Figure 41; (d) same as (c), but assuming that a radial age gradient exists in the Galactic bulge; (e) same as (c) for the model of the -8° field; (f) same as (d) for the model of the -8° field.

Figure 49: Comparisons of the photometry of the bulge giants in the -6° and -8° fields to the Baade's Window (BW) calibration relations. Crosses are giants with MK spectral types earlier than type M2; asterisks are giants designated as LPVs by Terndrup *et al.* (1990). Galactic bulge giants with MK spectral types M2 or later are represented by open squares for the field at $b = -6^{\circ}$ and by filled squares for the -8° field. The solid lines are the calibration relations derived for the BW giants (see Figures 33 - 35).

Figure 50: Comparisons of the -6° bulge giants to the Baade's Window calibration relations between $(H - K)_0$ and the molecular band indices. All symbols have the same meaning as in Figure 49. The solid lines are the BW calibration relations derived in Figure 36.

Figure 51: Comparisons of the -8° bulge giants to the Baade's Window calibration relations between $(H-K)_0$ and the molecular band indices. All symbols have the same meaning as in Figure 49. The solid lines are the BW calibration relations derived in Figure 36.

Figure 52: Comparisons of the -6° bulge giants to the Baade's Window calibration relations between $(H-K)_0$ and the atomic line indices. All symbols have the same meaning as in Figure 49. The solid lines are the BW calibration relations derived in Figure 38.

Figure 53: Comparisons of the -8° bulge giants to the Baade's Window calibration relations between $(H-K)_0$ and the atomic line indices. All symbols have the same meaning as in Figure 49. The solid lines are the BW calibration relations derived in Figure 38.

Figure 54: The photometry of the Galactic bulge models as a function of $(V - K)_0$. Circles represent Virgo elliptical galaxies, and triangles are Virgo lenticulars. The heavy solid lines are linear least-squares fits to the Virgo galaxy data (see Chapter 3); the dotted lines are the 99% confidence limits on the values of the dependent variable predicted by these relations. Open symbols are the galaxies NGC 4382 and NGC 4435, which have been excluded from the sample used to define the linear relations. The Baade's Window model results are represented by the numeral 4; see Table 30 for a description of this model. The numerals 6 and 8 show the locations of the 8.0 Gyr models of the Galactic bulge fields at $b = -6^\circ$ and $b = -8^\circ$, respectively.

Figure 55: The photometry of the Galactic bulge models as a function of $(J-K)_0$. All symbols and lines have the same meaning as in Figure 54.

Figure 56: The molecular band indices of the Galactic bulge models as a function of $(V-K)_0$. All symbols and lines have the same meaning as in Figure 54.

Figure 57: The molecular band indices of the Galactic bulge models as a function of $(J-K)_0$. All symbols and lines have the same meaning as in Figure 54.

Figure 58: The atomic line indices of the Galactic bulge models as a function of $(V-K)_0$. All symbols and lines have the same meaning as in Figure 54.

Figure 59: The atomic line indices of the Galactic bulge models as a function of $(J - K)_0$. All symbols and lines have the same meaning as in Figure 54.

CHAPTER V

DISCUSSION

In Chapter 4, the integrated colors and spectral feature strengths of three fields in the Galactic bulge were simulated. In this chapter, the properties of Galactic bulge stars and some of the uncertainties in the Galactic bulge models are further discussed. The basic Baade's Window model is compared to the Baade's Window model of Terndrup *et al.* (1990). In addition, the models are used to examine the radial gradients in the integrated light and stellar population of the Galactic bulge. The radial changes in atomic line widths and molecular band strengths are estimated from the models as a function of the color gradients in $(V - K)_0$ and $(J - K)_0$ and compared to the relations derived in Chapter 3 for the nuclei of E/S0 galaxies in the Virgo cluster. From this comparison, some of the characteristics of the stellar populations of the Galactic bulge and of early-type galaxies can be inferred.

5.1 The Baade's Window Model

In the basic Baade's Window (BW) model described in Chapter 4, the $(V - I)_0$ colors and I -band luminosity function (LF) for the bright giants ($I_0 < 15.25$) came directly from photometry of individual stars; for the fainter giants, subgiants and dwarfs, the average colors and magnitudes were taken from the $Z = 0.0100$, 8.0 Gyr isochrone of

VandenBerg (1985), and the LF was taken from a $Z = 0.0100$, $Y = 0.255$, 8.0 Gyr population model (Worthey 1994). Five alternate BW models were also presented which explored the effects of substituting an average color-magnitude relation (a ridge line) for the bright giant photometry and/or varying the I -band LF. In the following sections, various facets of these BW models are discussed, and the nature of the BW stellar population is examined in more depth.

5.1.1 Comparison to Previous Baade's Window Models

As shown in Chapter 4, the basic Baade's Window model reproduces quite well the colors and spectral feature strengths of the nucleus of a lower-luminosity early-type galaxy. In retrospect, this is probably what should have been expected. The Galactic bulge, in itself, is not as luminous as a bright elliptical galaxy, so if the stellar population of the Galactic bulge is analogous to that of a similar luminosity elliptical galaxy, then its integrated light should resemble that of a lower-luminosity E galaxy. On the other hand, even if the Galactic bulge population is typical of the stars in a giant elliptical galaxy, the distance of BW from the Galactic center makes its spectrum unrepresentative of the nuclear spectra obtained here for the Virgo galaxies. At the distance of the Virgo cluster (17.78 Mpc for $H_0 = 75 \text{ km sec}^{-1} \text{ Mpc}^{-1}$, using the best distance given by Faber *et al.* 1989), these nuclear spectra represent the regions within a radius of approximately 300 pc of each galaxy's center. However, Baade's Window, at $b = -3.9^\circ$, is about 550 pc from the Galactic center. Thus, under either set of circumstances, the integrated light of BW should not be expected to match the nuclear light of a giant elliptical galaxy.

In addition, the basic BW model is in accord with the integrated spectrum of BW obtained by Whitford (1978). Whitford measured a (3785 - 4250) color and the strengths of specific spectral features from blue ($\sim 3700 - 7500 \text{ \AA}$) spectral scans of BW, three early-type galaxies and the bulges of five spiral galaxies. Two of the early-type galaxies observed by Whitford turned out to be unusually blue and have correspondingly weak spectral features, while the colors and spectral feature measurements of the five spiral bulges and the elliptical galaxy NGC 3379 were more similar to one another. Although Whitford cautioned that the (3785 - 4250) color which he derived from his BW spectrum involved large corrections for reddening and foreground light, his color estimate for BW was bluer than the colors of the other spiral bulges and NGC 3379 but not as blue as the two very blue E/S0 galaxies. The strengths of the BW spectral features were generally appropriate for its color; interestingly, however, the integrated spectrum of BW had the deepest TiO absorption of any of the objects observed.

Thus, the relatively blue colors and weak spectral feature strengths of the basic BW model constructed here, when compared to the observations of early-type galaxy nuclei, appear to be consistent with the integrated spectrum of BW obtained by Whitford (1978). Why, then, were the BW models of FW87 and TFW, which incorporated much of the same data used here, able to match the colors and TiO band strengths of brighter ellipticals? Simple differences in the methodologies used to construct the models seem to have produced these differing results.

FW87 examined the effects of substituting BW M giants for the M giant populations used in existing galaxy synthesis models. They replaced the stellar population brighter than $M_{\text{bol}} = -1.2$ with the BW M giants in the models of Aaronson *et al.* (1978a) and Tinsley & Gunn (1976). These revised models were able to better match some, but not all, of the colors of a typical elliptical galaxy, and FW87 attributed the remaining disagreements to the differences in the properties of the BW stars and the model stars having $M_{\text{bol}} > -1.2$. To match the colors of a luminous E/S0 galaxy, FW87 adjusted the colors and brightness of the Tinsley & Gunn stellar population fainter than $M_{\text{bol}} = -1.2$ in a manner consistent with the supersolar metallicity believed to apply to BW stars. Making the integrated light of these stars redder in $V - K$ and $J - K$ and fainter in K , their models were much better able to reproduce the characteristics of a bright early-type galaxy.

TFW extended the work of FW87 by constructing an entirely empirically-based model of BW. In a manner similar to what was done here, they constructed: (1) a mean I_0 , $(V - I)_0$ sequence, (2) a Cousins I -band luminosity function, and (3) calibration relations to predict $(V - K)_0$, $(J - K)_0$, $(H - K)_0$ and BC_I from $(V - I)_0$. Using this information, TFW determined a bolometric LF and built an integrated Galactic bulge model for the stellar population fainter than $M_{\text{bol}} = -1.2$. To this they added the BW M giant population from FW87, assuming that these M giants contributed 66% of the K -band flux, as they had in the FW87 models. TFW then derived integrated TiO band strengths for their model and were able to reproduce the features of a bright elliptical galaxy remarkably well.

Why does the BW model built here differ so dramatically from that of TFW? To examine this question, the basic BW model described in Chapter 4 was split into two components - the M giants and the rest of the stars. Due to the good correlations between MK spectral type and $S(7890)$ and between $S(7890)$ and $(H - K)_0$, the M-giant/K-giant split was made at constant color. This color was determined as follows: (1) a third-order polynomial was fit to the $S(7890)$ vs. MK spectral type diagram for field giants, deleting early-K giants as deemed necessary until the fit matched the late-K giant to late-M giant data reasonably well (the quadratic fit seen in Figure 23 cannot be reliably extrapolated to spectral types earlier than M2); (2) the $S(7890)$ value appropriate to an M0.5 star was found to be 0.0512 mag.; and (3) the calibration relations used in the basic BW model translated this $S(7890)$ index into an $(H - K)_0$ color of 0.140 mag. and, thus, $(V - I)_0 = 1.452$. Using the BW photometry shown in Figure 60, an integrated M-giant model was constructed of the stellar population redder than $(V - I)_0 = 1.452$; the stars included in this model lie within the dotted box but redward of the vertical dashed line in Figure 60.

The resulting BW M-giant model consisted of 196 stars, and the integrated colors of this model are given in Table 38; this table also presents the TFW BW model colors. It is clear from Table 38 that, even though the TFW and basic BW models incorporate different spectral type classification schemes and the M giants have been designated on the basis of color here rather than using bolometric luminosity (as in TFW), the integrated colors of the M giant populations of the two models are not substantially different, nor are the integrated colors of the non-M-giant component of

the models. The difference in model results can be attributed entirely to the relative contributions of these M-giant and non-M-giant populations to the integrated light. While TFW assumed that 66% of the light at K is contributed by the M giants, the M giants in the basic BW model constructed here only produce 51% of the K -band flux. The lower section of Table 38 shows the integrated colors which result when the M giant K -band flux is increased in the basic BW model, leaving the K -band flux of the rest of the model unchanged, until the contribution of the M giants to the total luminosity at K reaches 66%; the colors of this model now match the TFW model colors much more closely.

All in all, the basic BW model described in Chapter 4 should be more representative of the integrated light of BW than either the FW87 or TFW models because it completely and consistently models the entire BW stellar population simultaneously. Specifically, the models built here: (1) include the fainter BW stars not observed by FW87 and ,therefore, require no *ad hoc* adjustments to match the characteristics of different pieces of the stellar population, and (2) model the population of BW as a whole, naturally giving the contributions of the various subpopulations as a function of wavelength and, thus, do not require assumptions about the relative contribution of the M giants to the K -band light, such as TFW used to sum the BW models for the M giants (FW87) and the fainter stars. Overall, the BW model built here is the best model of BW constructed to date.

5.1.2 The Distance to the Galactic Bulge

In developing the Galactic bulge models, the distance to the Galactic center was assumed to be 8.0 kpc (Reid 1993). Although this distance was only used to transform the VandenBerg (1985) isochrones and the giant branch ridge lines of Terndrup (1988) from M_I to I_0 , is it consistent with the observational data used to model the Galactic bulge? This can be tested by computing the surface brightness fluctuation magnitude for the basic BW model.

The concept of the fluctuation magnitude stems from the luminosity fluctuation, $\bar{L}$, defined by Tonry & Schneider (1988) to be

$$\bar{L} = \frac{\sum n_i L_i^2}{\sum n_i L_i} \quad (6)$$

where n_i is the number of stars of luminosity L_i in the stellar population. The conversion from fluctuation luminosity to fluctuation magnitude is done in exactly the same manner as stellar luminosity is converted to stellar magnitude, and the distance, d , to an object (in pc) can be determined from its apparent fluctuation magnitude, $\bar{m}$, through

$$\bar{m} - \bar{M} = 5 \log d - 5, \quad (7)$$

if its absolute fluctuation magnitude, $\bar{M}$, is known.

Using the Revised Yale Isochrones (Green *et al.* 1987) to model the effects of stellar population differences on fluctuation magnitudes in the V , R and I bands, Tonry *et al.* (1990) found that $\bar{M}_I$ is very insensitive to changes in the age, metallicity, helium abundance, IMF exponent and structure of the horizontal branch for stellar

populations with $[\text{Fe}/\text{H}] > -1.5$. This implies a characteristic $\bar{M}_I$, which means that the distance to a galaxy can be found by simply measuring $\bar{m}_I$. Surface photometry of a group of early-type galaxies in the Virgo cluster by these same authors confirmed the relative invariance of $\bar{M}_I$.

What is this characteristic value of $\bar{M}_I$? To date, four calibrations have been developed for $\bar{M}_I$. The original calibration (Tonry *et al.* 1990) was based on the Revised Yale Isochrones (Green *et al.* 1987) but was shifted in zero point so that a distance of 0.70 Mpc resulted for M32. Another (Tonry 1991) was derived empirically from observations of galaxies in the Local Group, the Fornax cluster and the Eridanus cluster whose distances are known from Cepheid variables; its zero point was set by the fluctuation magnitudes measured for M32 and the bulge of M31, assuming a distance of 0.77 Mpc to each. The other two methods (Ajhar & Tonry 1994) stem from measurements of $\bar{m}_I$ in globular clusters, whose distances were derived from their metallicities, assuming a specific relationship between $[\text{Fe}/\text{H}]$ and the luminosity of the horizontal branch; these two methods differ only in the $M_V(\text{HB})$, $[\text{Fe}/\text{H}]$ calibrations used.

The apparent fluctuation magnitude predicted from the color-magnitude diagram used in the basic BW model (Figure 24) is $\bar{m}_I = 12.967$. Using the globular cluster calibrations for $\bar{M}_I$ gives $R_0 = 9.6 - 9.9$ kpc, while the calibrations of Tonry *et al.* (1990) and Tonry (1991) give $R_0 = 7.8$ kpc and $R_0 = 7.4$ kpc, respectively. Assuming that the uncertainties in $\bar{m}_I$ and $\bar{M}_I$ are 0.10 mag. and 0.25 mag., respectively, these distances are good to 10%, and any of the four calibrations gives a value for R_0 which

differs from 8.0 kpc by less than 2σ .

Since the integrated spectrum of BW resembles that of an E/S0 galaxy (Whitford 1978), it is perhaps not surprising that the surface brightness fluctuation method gives a distance to the Galactic center near 8.0 kpc, especially when the early-type galaxy calibration for $\bar{M}_I$ is used. Nevertheless, since the utility of modelling the integrated light of the Galactic bulge was based upon the premise that the stellar population there is similar to the stellar population of an early-type galaxy, it is reassuring to find that the fluctuation magnitude calculated for the basic BW model implies a distance to the Galactic bulge which agrees with current estimates (Reid 1993).

5.1.3 The Baade's Window Color-Magnitude Diagram

Although the basic Baade's Window model described in Chapter 4 produces a reasonably good match to the colors and spectral feature strengths of a low-luminosity elliptical galaxy, the BW color-magnitude diagram (CMD) is obviously not that of a simple, homogeneous stellar population. As mentioned in Chapter 4 and shown in Figure 60, this is most evident at the brightest I_0 magnitudes, where the CMD splits into two or three giant branch sequences. Are all of these bright stars actually members of the Galactic bulge?

Radial velocity measurements (Sharples *et al.* 1990) show that the velocity dispersion of the BW M giants fainter than $I = 11.8$ ($I_0 = 10.736$) is similar to the velocity dispersion of a variety of other Galactic bulge subpopulations; this luminosity is represented by the horizontal dashed line in Figure 60. However, the group of M giants brighter than $I = 11.8$ have a smaller velocity dispersion than the other M giants

and probably lie along the line of sight to BW. Since only four of these probable field stars were mistakenly included in the basic BW model, this model should accurately represent the bright, red stellar population of BW.

Could the bluest of the giant branches in the BW CMD represent some type of contaminating non-bulge population? This is a possibility. Space velocities (Terndrup *et al.* 1995) indicate that a significant fraction of these stars may not be located in the Galactic bulge. In addition, this group of stars appears very similar in color and luminosity to those near the tip of the giant branch in the $l = 0^\circ$, $b = -10^\circ$ field observed by Terndrup (1988). A giant branch ridge line representing this -10° field was estimated from the optical CMDs of Terndrup (1988) in exactly the same manner described for the three bulge fields modelled in Chapter 4. This ridge line is compared to the BW CMD and the BW ridge line in Figure 60, and it is a very good representation of the “bluest” BW giant branch.

Because the Galactic bulge population may show a change in character between the -8° and -10° fields (Terndrup *et al.* 1990, Tyson 1991), this sequence of stars could consist of some type of non-bulge population. In fact, when the -10° giants from TFW are plotted in the $(J-H)_0$ vs. $(H-K)_0$, CO vs. $(H-K)_0$ and TiO index vs. $(H-K)_0$ diagrams, they agree better with the field giant trends than with the BW calibration relations. This result, however, is uncertain; the TFW giants located at $b = -12^\circ$ agree with the BW calibration relations for TiO index vs. $(H-K)_0$, and a simple change in the assumed reddening for the -10° field from $E_0(B-V) = 0.18$ (FTBW) to the value $E_0(B-V) = 0.21$ used by Terndrup (1988) would remove the discrepancies between

the -10° and BW trends in all but the $(J - H)_0$ vs. $(H - K)_0$ diagram. Nevertheless, careful inspection of the data indicates that it more probable that the reddening used by FTBW for the -12° field, which was inferred from the reddening maps of Burstein & Heiles (1982), is slightly too high. Using the FTBW reddening values, the trends exhibited by the -10° giants are consistent with the field giant relations in all of the color-color and color-TiO plots; the -12° giants are better fit by the BW calibration relations when TiO or CO are plotted vs. $(H - K)_0$ but lie bluer than the field giants in $(H - K)_0$ when H_2O or $(J - H)_0$ are considered. A slight decrease in the reddening assumed for the -12° field can bring the stars there into consistent agreement with the field giant trends.

Because the Galactic bulge membership of this population of bright, blue stars is suspect, it was deemed important to examine this situation further. To do so, a new BW model was constructed in which the bright, blue stellar population of the basic BW model was omitted. The stars to be omitted were determined by consulting a K_0 , $(J - K)_0$ CMD of a BW field (Tiede *et al.* 1995); infrared CMDs do not show the giant branch curvature caused by molecular blanketing in the optical bands and, therefore, allow a much more precise determination of the giant branch tip. From this CMD, the tip of the giant branch was estimated to lie at $K_0 \sim 7$, $(J - K)_0 \sim 1.3$. For BW giants, Tiede *et al.* show that $(J - K)_0 \sim 1.3$ corresponds to $(V - K)_0 \sim 7$, giving a giant branch tip magnitude of $V_0 \sim 14$. The new BW model was then constructed and included only giants fainter than approximately $V_0 = 14$; this revised selection criterion is shown as the solid boxed area in Figure 60, while that used previously for

the basic BW model is shown as a dotted box.

The model constructed without the bright, blue stars turned out to have bluer colors and weaker molecular bands than the basic BW model and did not overlap the nuclear measurements of any of the early-type galaxies observed. While this seems counterintuitive, it is easily understood. Even though the excluded stars are the bluest at their I magnitude, they are still redder, on average, than the majority of the fainter giants. In fact, this group of 73 stars has the integrated colors and TiO band strengths of about an M3 giant; in the basic BW model, they contributed $\sim 13\%$ of the I -band flux and $\sim 20\%$ of the K -band light. In other words, this group of stars is an integral part of producing the match between the integrated light of the basic BW model and that of a low-luminosity early-type galaxy.

In addition, the fluctuation magnitude, $\bar{m}_I$, of this revised model implied a much larger distance to the Galactic bulge than the basic BW model did. Using either of the globular cluster calibrations of Ajhar & Tonry (1994) gave $R_0 = 14.0$ kpc, while the calibrations based upon early-type galaxies (Tonry *et al.* 1990, Tonry 1991) gave 10.6 and 11.3 kpc, respectively. Thus, if the assumption that the stellar population of the Galactic bulge is similar to that of an early-type galaxy is still valid, then either: (1) the bright, blue stars are members of the Galactic bulge, or (2) the bright, blue stars are “field” stars and there exists an approximately equal percentage of “field” star contamination at all magnitudes, such that the shape of the I -band luminosity function does not differ significantly from that derived from the CMD stars included in the basic BW model. While the latter expectation is reasonable, the data discussed

here cannot discriminate between these two possibilities or even determine if either is applicable.

5.1.4 The Baade's Window Luminosity Function

Four possible *I*-band luminosity functions were presented for BW in Chapter 4 - an empirically-based LF (TFW), a theoretical LF (Worthey 1994), and two LFs in which the bright end ($I_0 < 15.25$) was taken from the BW CMD (Figure 24) and either the TFW or Worthey LF was used fainter than this. After normalization, one of the main differences between these LFs was the number of stars in the brightest two magnitudes of the LF; the upper LF derived from the CMD had a fainter magnitude cutoff than either the TFW or Worthey LF.

In Chapter 4, it was decided that the “best” LF to use in the basic BW model was the merged CMD/Worthey representation; the reasons that the Worthey LF was preferred over the TFW LF for the fainter stars is discussed there. The CMD LF is considered to more accurately represent the bright stars because: (1) it comes directly from the observational data and is consistent with the Sharples *et al.* (1990) membership cutoff magnitude for the BW M giants; (2) the TFW LF is not consistent with the Sharples *et al.* data and is thus probably affected by field star contamination at the bright end; and (3) Worthey derived his LF by applying bolometric corrections (BCs) to the Revised Yale Isochrones (Green *et al.* 1987), for which the *I*-band BCs are suspected of being in error (Tonry 1991, Ajhar & Tonry 1994); these BCs produce too little curvature at the tip of the *I*-band giant branch. For these reasons, only the BW models using the merged CMD/Worthey LF, the basic BW model (model C)

and model w, are considered below in comparisons with early-type galaxy nuclei.

5.1.5 The Metallicity of the Baade's Window Stars

A great amount of work has been done to determine the properties of the Galactic bulge stellar population. This research has concentrated on the stars in Baade's Window and has shown that the stars in the Galactic bulge differ significantly from their solar neighborhood counterparts; the color-color and color-spectral feature diagrams presented in Chapter 4 (Figures 31 - 39) also make this apparent. What is the nature of the difference between the bulge and local disk stars?

The majority of data is consistent with and has been interpreted as indicating that the Galactic bulge stars are super-metal-rich (SMR), where SMR usually denotes $[\text{Fe}/\text{H}] > 0$. A brief review of this evidence follows:

- *JHK* photometry (Frogel & Whitford 1982, 1987, hereafter FW82 and FW87, respectively; Frogel *et al.* 1990, hereafter FTBW; see Figure 33 as well) shows that, at a given $(H - K)_0$, the bulge M giants tend to be bluer in $(J - H)_0$ than the field giants, while the trend followed by globular cluster giants, which are more metal-poor than the field giants, is at redder $(J - H)_0$ than the field star relation (Cohen *et al.* 1978).
- measurements of the $2.3\ \mu\text{m}$ CO band (FW82, FW87, FTBW; see Figure 34 as well) show that the bulge giants have enhanced CO absorption with respect to field giants of the same color.

- Washington photometry (Tyson 1991, Geisler & Friel 1992) indicates that bulge stars are SMR on average.
- low-resolution spectroscopy of Galactic bulge K giants (Whitford & Rich 1983, Rich 1988) shows enhanced Fe abundances in these stars with respect to the solar abundance.
- spectroscopy of Galactic bulge M giants (TFW; see Figure 36 as well) indicates that TiO absorption is stronger in bulge stars than in field giants of the same color.
- the K/M giant ratio in the Galactic bulge is much lower than anywhere else in the Galaxy, indicating that the giant branch, which gets redder as metallicity increases, is so cool that it extends significantly into the M-giant regime.
- the C/M giant ratio is very low in the Galactic bulge (Blanco *et al.* 1978, Blanco *et al.* 1984); as Aaronson (1986) describes, the C/M ratio is metallicity dependent because (1) the aforementioned giant branch cooling as metallicity increases makes M stars more prevalent at high metallicity, and (2) carbon stars are more difficult to produce at high metallicity because the increased oxygen abundance requires that a greater amount of carbon must be mixed into the stellar atmosphere to produce $C/O > 1.0$.
- the optical color-magnitude diagrams of Terndrup (1988) imply an approximately solar metallicity for BW from: (1) the color difference between the BW

giant branch and that of the Galactic globular cluster 47 Tuc, and (2) the color of the BW giant branch at the luminosity of the horizontal branch.

Two major pieces of evidence have contradicted the interpretation that Galactic bulge stars are SMR - one is the recent work of McWilliam & Rich (1994), which is discussed below, and the other is the position of the BW giant branch in the CMD. If the stars in BW are old and the general trend exhibited by globular cluster giant branches and predicted theoretically is extended into the SMR domain, then the BW giant branch should be much redder than it is. For example, in the K_0 , $(J - K)_0$ color-magnitude diagram, the BW giant branch occupies approximately the same position as the giant branch of the globular cluster 47 Tuc (FW82, FW87), which has $[\text{Fe}/\text{H}] \sim -0.6$. Because of the evidence discussed above for the enhanced metallicity of the bulge giants, this CMD anomaly has previously been attributed to differential blanketing effects; in other words, the colors no longer accurately reflect the true effective temperatures of the BW giants due to the SMR nature of these stars. The McWilliam & Rich data lend credence an alternate explanation, selective enrichment.

Consulting the BW calibration relations developed in Chapter 4 (see Figures 31 - 38), it is apparent that the BW and field giant relations tend to change slope at the approximate junction of the K and M giants. Because these changes are caused by differential blanketing and they occur at bluer colors in the BW giants than in the field giants, these diagrams are also consistent with a supersolar metallicity in BW stars. Note, however, that in only two instances do the K giants in BW follow obviously different trends than the field K giants; these differences occur in the CO,

$(H - K)_0$ and $(I - K)_0$, $(H - K)_0$ diagrams (Figures 32 and 34, respectively).

Rather than invoking an overall metallicity enhancement in the Galactic bulge, the best current explanation for the difference between BW giants and giants in the solar neighborhood appears to be selective enrichment of the light elements in Galactic bulge stars. McWilliam and Rich (1994) obtained echelle spectra at a resolution $R = 17,000$ of 11 K giants in Baade's Window. They illustrated the effects of CN blanketing on stellar spectra and emphasized the importance of accounting for CN when measuring the strengths of other spectral features. By concentrating on atomic lines which were not contaminated by CN, they found an average $[\text{Fe}/\text{H}] = -0.25$ for the BW K giants but $[\text{Mg}/\text{Fe}]$ and $[\text{Ti}/\text{Fe}] \sim +0.3$ dex. They also stated that these stars do not have enhanced CN, although they do not substantiate this claim quantitatively.

The results of McWilliam & Rich (1994) are important because it is possible to explain all of the observational data for the BW giants by a simple enhancement of Ti and the CNO elements with respect to Fe. In fact, many stars which have been initially classified as being SMR have later been found to simply have strong CN. For example, Keenan *et al.* (1987) spectroscopically classified 50 stars claimed to be SMR by Spinrad & Taylor (1969). They found that, when assigned spectral classes on the revised MK system, nearly all of these stars required positive CN indices but few had unusually strong Ca or Fe line strengths with respect to normal Population I stars.

However, to justify the claim that the observational data can be completely explained by light element enhancements in the Galactic bulge stars, a reexamination of each of the pieces of information used previously to infer that the Galactic bulge stars are SMR is necessary:

- *JHK* photometry: Terndrup *et al.* (1991) used infrared spectroscopy of BW M giants to examine the blanketing effects in the *J*, *H* and *K* bands. They concluded that the difference between Galactic bulge and field giants in the $(J-H)_0$, $(H-K)_0$ plane was due to increased blanketing in the *H* band in bulge giants, but they discounted both CO and H₂O as possible agents. However, the conclusion that CO was not the absorber responsible for the *H*-band blanketing was based upon: (1) a comparison of the positions of the lines making up the second overtone (3-0) CO band to the positions of observed lines in the Galactic bulge giant *H*-band spectra, and (2) the expectation that this CO band would appear similar to the first overtone band in the *K* window, having the greatest absorption at the bandhead and decreasing absorption redward of this. Since the *H*-band spectra of the BW M giants did not show this expected pattern of absorption, it was concluded that CO was not the absorber in question. However, Origlia *et al.* (1993) have shown that the structure of the second overtone (3,0) band is not the same as that of the first overtone band, having a more trough-shaped structure with maximum absorption between 1.6 and 1.65 μm . Because this matches the blanketing trend seen in the bulge M giants, CO again appears to be a likely candidate for the *H*-band mystery absorber

of Terndrup *et al.* On the other hand, CN also blankets the *H*-band (see *e.g.* Wing & Spinrad 1970), and enhanced CN has been shown both observationally (Smith 1988) and theoretically (McGregor & Hyland 1981) to produce a color shift in the *JHK* plane similar to that seen between the bulge and field giants. However, Origlia *et al.* show that the CN band basically just depresses the flux at the blue end of the *H* band and does not have the structure of the absorption band seen in the BW M giants. In either case, an enhancement of the CNO elements in bulge stars can explain the bulge/field star differences in the *JHK* plane.

- the 2.3 μm CO band: if the Galactic bulge giants have greater CNO abundances than field stars, they would presumably have stronger CO absorption at a given color.
- Washington photometry: the Galactic bulge star metallicities were inferred from the $C - T_1$ index, which measures the strength of the CN band near 3900 Å, so a CN enhancement in the BW stars will make them appear to be SMR on the Washington system. Note that the same tendency would probably result, although to a lesser extent, from colors involving the Washington *M* filter because it measures a combination of Mg and Fe features, and Mg also appears to be enhanced with respect to Fe in BW K giants (McWilliam & Rich 1994).
- quantitative spectroscopy of Galactic bulge K giants: the McWilliam & Rich (1994) analysis supercedes the work of Rich (1988) and shows that the metal-

licities derived from the spectroscopy of Rich were biased to higher $[\text{Fe}/\text{H}]$ by CN contamination of the Fe lines and by the enhanced Mg/Fe ratio in the bulge stars.

- spectroscopy of Galactic bulge M giants: bulge M giants would have deeper TiO bands than field giants of the same color because they have higher $[\text{Ti}/\text{Fe}]$.
- the K/M giant ratio: this is naturally explained by the Ti enhancement. Instead of the giant branch getting cooler due to increased overall metallicity, the temperature boundary between K and M giants becomes hotter.
- the C/M giant ratio: this is also a natural result of the increase in Ti abundance because M giants become more prevalent.
- the optical color-magnitude diagrams: as Terndrup (1988) notes, the BW optical CMD is consistent with subsolar $[\text{Fe}/\text{H}]$ if the reddening and distance modulus are changed to the values adopted here for BW.

Note that selective enrichment of CNO in the Galactic bulge also explains why the field and BW K giants differ significantly in the $(I - K)_0$, $(H - K)_0$ diagram (see Figure 32); this difference can be attributed to enhanced CN absorption in the I band for the BW giants. It is also consistent with the fact that an 8.0 Gyr, $[\text{Fe}/\text{H}] = -0.23$ isochrone provided the best fit to the BW subgiant branch and main-sequence turnoff in Chapter 4. However, the key feature of the selective enrichment scenario for the Galactic bulge is that it can simultaneously explain the observational data discussed above and the color of the BW giant branch. Overall, it neatly ties all of the empirical

data together. Obviously, it is now extremely important to either verify or refute this speculation through quantitative measurements of the CNO abundances of Galactic bulge stars.

5.1.6 Comparison to E/S0 Galaxy Nuclei

Figures 42 - 47 compared the various BW models to the trends exhibited by the E/S0 galaxy nuclei in the Virgo cluster. As mentioned previously, only the basic BW model (model C) and BW model w will be discussed in comparison to the galaxy data. Recall that these two models differ only in their representation of the BW giant branch; the basic BW model uses stellar photometry for $I_0 < 15.25$, while model w incorporates a ridge line there.

In most of the color-color and color-index plots, BW models C and w appear to match the integrated light of a normal, low-luminosity elliptical galaxy. The dotted lines shown in Figures 42 - 47 are the 99% confidence limits on $\hat{y}$, the value of the dependent variable predicted by the linear fit to the data. In comparing the BW models and galaxy nuclei, it is important to recall that the improper weighting of the I(7100) feature in the models and the reddening sensitivity of the S(7890) index are responsible for the mismatches in the diagrams involving those indices (see Section 4.3.2); also, the atomic line pseudo-equivalent widths predicted by the models only differ from the galaxy measurements because these model indices have not been adjusted to the velocity dispersion of the galaxy data. Keeping these considerations in mind, it is apparent that BW models C and w lie within the 99% boundaries in nearly all of the diagrams. The exceptions are:

- the BW models are either bluer in $(J - K)_0$ or redder in $(V - K)_0$ than the galaxy nuclei in the $(J - K)_0$, $(V - K)_0$ diagram.
- the BW models are either bluer in $(H - K)_0$ or redder in $(V - K)_0$ than the galaxy nuclei in the $(H - K)_0$, $(V - K)_0$ diagram.
- BW model C has a slightly weaker I(7890) index than an E/S0 nucleus of its $(V - K)_0$ color or is redder in $(V - K)_0$ than a galaxy of similar TiO strength.

Overall, the conclusion reached from a comparison of BW models C and w to the observations of the nuclei of early-type galaxies in the Virgo cluster is that these models are actually a very good match to a low-luminosity E/S0 galaxy. As mentioned previously, this is a reasonable expectation. The question remains, however, of how to represent the integrated light of a brighter elliptical galaxy. Is the difference between the BW models and a giant elliptical due strictly to the fact that we are sampling different physical regions of the Galactic bulge and the Virgo galaxies observed (*i.e.* ~ 550 pc from the Galactic center *vs.* the inner ~ 300 pc in the Virgo galaxies)? If not, how must the stellar population in BW change in order to produce the integrated characteristics of a brighter E/S0 galaxy? These questions are explored below.

5.2 Radial Gradients in the Galactic Bulge

The Galactic bulge models constructed in Chapter 4 produce colors and spectral indices which imply that radial gradients exist in the integrated light and stellar population of the Galactic bulge. However, it is important to keep in mind that these model gradients are produced only by shifting the color-magnitude relation of

the stellar population as a function of latitude - the *I*-band luminosity function and the calibration relations used to derive the colors and spectral indices have not been varied. This is only reasonable because there is no conclusive evidence that either of these other model components varies with latitude.

Is a changing CMD but non-varying LF and calibration relations consistent with any possible stellar population variation? Since the giant branch gets bluer with increasing latitude in the Galactic bulge, three possibilities come to mind for how the bulge stars may change as one moves outward from the Galactic center: (1) they may be getting more metal-poor on average; (2) they may be getting younger on average; or (3) their abundance ratios may be changing. While the apparent change in slope of the giant branch with latitude may be most consistent with a drop in metallicity between BW and the outer fields, the models of Chapter 4 imply that the metallicity difference between BW and the -8° field is extremely modest (< 0.10 dex in $[\text{Fe}/\text{H}]$). A comparison of solar-metallicity giant branches from the Revised Yale Isochrones (Green *et al.* 1987) indicates that an age gradient would also be consistent with the general change in giant branch morphology in the CMD. Since the effects of changing abundance ratios on the color and slope of the giant branch are unknown, no definite conclusion can be reached regarding the cause of the radial stellar population gradients in the Galactic bulge. A further exploration of the possibilities is beyond the scope of this thesis.

Nevertheless, the inferred Galactic bulge gradients can be used to explore two important questions. First, would an extension of these gradients to $b = -1^\circ$ predict

that a spectrum of the inner Galactic bulge would match the nuclear spectrum of a giant E/S0 galaxy? Second, how do the changes of various spectral features with color in the Galactic bulge compare to the trends seen among the nuclei of early-type galaxies of differing luminosity? Each of these questions is examined in the following sections.

5.2.1 Simulating the Inner Galactic Bulge

To explore the integrated light of the inner Galactic bulge, radial gradients were derived from the colors and spectral indices of the $Z = 0.0084$, 8.0 Gyr model of the $b = -8^\circ$ field and those of both the basic BW model (model C) and BW model w. Gradients were derived using each of these BW models because, given the current data, it cannot be determined which gradient most accurately represents the radial trends in the Galactic bulge. The basic BW model probably best represents the integrated light of BW, but the methodology used to build BW model w, which utilizes a giant branch ridge line, is more consistent with that used for the -8° field. Presumably, the differences between BW models C and w are caused by choosing a ridge line for model w which does not represent the actual stellar color-magnitude distribution in BW well, especially at the top of the giant branch. This may simply be due to errors in placing the ridge line properly and could be overcome by “tweaking” this ridge line. On the other hand, the ridge line chosen may be a reasonable representation of the BW giant branch but the models differ because the BW CMD cannot be well-represented by *any* single ridge line. If random errors in placing the ridge line dominate, then the “best” model in each field should be used to estimate the radial

gradients; this case would call for the use of model C for BW. If systematic effects dominate, then it is critical to use models which are constructed as consistently as possible, and the use of BW model w would give the most representative gradients.

Overall, the situation is this: the ridge line used to represent the BW giant branch is not well-chosen due to the scatter in the BW CMD at the tip of the giant branch. Thus, a systematic difference results between the results of BW models C and w. If such an effect is also important in the -8° CMD, then the gradients should be determined using BW model w. However, if the CMD scatter is sufficiently reduced that the ridge line can be better determined at $b = -8^\circ$ than in BW, as appears to be the case in the optical CMDs of Terndrup (1988), then the gradients should involve the basic BW model. For completeness, each of these alternatives is examined.

Since color and spectral feature gradients in elliptical galaxies are usually found to be linear in $\log(\text{radius})$, the radial gradients in the Galactic bulge were also computed in this manner and then extrapolated to estimate the integrated colors and indices of a field at $b = -1^\circ$ (~ 140 pc from the Galactic center). This allows an estimation of whether the inner Galactic bulge resembles the nucleus of a bright elliptical galaxy. Some caveats to keep in mind in this process are:

- the estimated gradients are based upon only two points, so both the radial gradients themselves and their extrapolations are highly uncertain,
- the true gradients may not actually be linear in $\log r$,
- the gradients in $I(7100)$ may be in error because the effects of improperly weighting the $I(7100)$ indices in the models are unknown, and

- the atomic line indices predicted by the models have not been normalized to a common velocity dispersion (although the velocity dispersion of the stellar population of the Galactic bulge is not believed to be a strong function of radius).

The colors and spectral indices which result from extrapolations of the radial gradients predicted by the Galactic bulge models are shown in Figures 61 - 66. In these figures, the BW models are represented by the symbols “C” and “w”, the -8° model is shown as an “8”, and the inferred colors and indices of the $b = -1^\circ$ field are shown as “1”s; the radial trends of the Galactic bulge models are represented by the dashed lines connecting these symbols. For comparison, the Virgo galaxy data and the linear fits to this data are also reproduced in Figures 61 - 66.

In general, the extrapolations to -1° do not match the integrated light of an E/S0 galaxy. This disagreement is primarily due to two factors: (1) the large apparent radial gradient in $(V - K)_0$ in the Galactic bulge, which causes the extrapolated $(V - K)_0$ colors to be redder than any of the E/S0 galaxy nuclei, and (2) the differences in slope of the radial trends in the Galactic bulge models and the observed luminosity trends in the early-type galaxies. Although the uncertainties in the extrapolations definitely influence this disagreement as well, it is safe to conclude that either: (1) the gradients or their extrapolations are incorrect, or (2) the integrated spectrum of the inner Galactic bulge does not resemble the integrated spectrum of the nucleus of an early-type galaxy in the Virgo cluster. In fact, the most important point which Figures 61 - 66 illustrate is that the color-index trends as a function of radius in the

Galactic bulge often differ from the relations along a luminosity sequence of E/S0 galaxy nuclei. Specific differences in these relations are discussed further below.

5.2.2 Comparison to E/S0 Galaxy Nuclei

Early-type galaxies exhibit stellar population gradients in two ways. Colors and line strengths are known to vary systematically within individual galaxies and also between the nuclei of galaxies of differing luminosity. Each of these types of gradients has been extensively studied, if not yet completely understood. In this section, the radial stellar population gradients inferred from the Galactic bulge models of Chapter 4 are compared to the changes seen in the Virgo E/S0 galaxies of different luminosity (Chapter 3).

As discussed in Chapter 1, the well-known color-magnitude relation exhibited by early-type galaxies, in which brighter galaxies tend to be redder than less luminous galaxies, was first studied systematically by Visvanathan & Sandage (1977). Since that time, many other studies have attempted to ascertain the universality of this relation (see Chapter 1), which has generally been attributed to an increase in metallicity, and thus increased blanketing and a general cooling of the giant branch, in the brighter galaxies (Faber 1977).

In addition, most early-type galaxies possess internal color gradients, with the nuclear regions being redder than the outer regions. For example, Peletier *et al.* (1990a, 1990b) measured color gradients in a large sample of elliptical galaxies. Peletier *et al.* (1990b) also compared the ratios of the radial $U - V$ and $V - K$ color gradients within the galaxies to the ratio of these colors along the respective color-magnitude

relations. They found reasonable agreement between the two and concluded that both were probably caused by variations of the same parameter, namely metallicity.

However, spectroscopy indicates that the relationship between these two types of gradients is more complex. Radial gradients within galaxies have now been detected and measured for a number of specific spectral features, and the behavior of these features has also been examined among galaxy nuclei of different luminosity. Burstein *et al.* (1984) measured optical line strengths for the nuclei of a large sample of E/S0 galaxies and for Galactic globular clusters. They defined two indices which have become “standards” for metallicity studies - Mg_2 , which measures a combination of the MgH band and Mg *b* line near 5200 Å, and $\langle Fe \rangle$, the sum of the strengths of the Fe lines at 5270 and 5335 Å. Burstein *et al.* found that the globular clusters followed a different $\langle Fe \rangle$ vs. Mg_2 relationship than the elliptical nuclei; for a given change in Mg_2 , the change in $\langle Fe \rangle$ is much larger among the globular clusters than between the E/S0 galaxy nuclei.

More recently, work on gradients within early-type galaxies have found that the radial Mg_2 , $\langle Fe \rangle$ trends are similar in slope to the globular cluster trends (Gorgas *et al.* 1990, Davies *et al.* 1993, Davidge 1992, Worthey *et al.* 1992, Gonzalez 1992). The interpretation now appears to be that color and spectral feature differences between galaxy nuclei are being produced by a change in abundance ratios, with Fe abundances changing little but light element (CNO, α element) abundances increasing with galaxy luminosity. However, within each individual galaxy, the gradients are more likely produced by a change in the overall metallicity of the stellar population, in which

all of the metals vary more-or-less in lockstep. The evolutionary synthesis models of Worthey (1994) support this scenario. Do the Galactic bulge models agree?

Table 39 presents a quantitative, statistical comparison of the slopes of the color-color and color-index relations predicted by the Galactic bulge models and those derived from the observations of the nuclei of early-type galaxies in the Virgo cluster. To compare the models and observations, the standard error of the slope of the linear fit to the Virgo galaxy nuclei and a standard t -test were used to place 99% confidence limits on this slope. Then, for any given relation, if the slope predicted by the Galactic bulge models does not lie within these 99% confidence limits, the radial color-color or color-index relation in the Galactic bulge is considered to be different from that exhibited by the E/S0 galaxy nuclei. Those trends which have Galactic bulge and E/S0 galaxy slopes which differ significantly are underlined in Table 39.

Overall, the main conclusions to be drawn from Table 39 are:

- the Na I-color, Ca8498-color and I(8197)-color relations are different in the Galactic bulge and the Virgo galaxies, regardless of which BW model is used to estimate the radial gradients in the Galactic bulge.
- the I(7890), S(7890) and I(8460) gradients as a function of $(J - K)_0$ are significantly steeper as a function of radius in the bulge than they are along a luminosity sequence of early-type galaxies.
- the I(7890), S(7890) and I(8460) gradients as a function of $(V - K)_0$ are significantly steeper as a function of radius in the bulge than they are along a

luminosity sequence of E/S0 galaxies when the Galactic bulge gradients are estimated from the -8° model and the BW model w.

Each of these differences will now be examined in turn.

Ca8498

The differences between the Ca8498, $(J - K)_0$ and Ca8498, $(V - K)_0$ trends in the Galactic bulge and in the E/S0 nuclei are due to the differing velocity dispersions of the models and the observed data. When the Ca8498 indices measured from the *observed* galaxy spectra, which have not been broadened to a common velocity dispersion, are plotted *vs.* color, the slopes of the E/S0 nuclear trends and the Galactic bulge relations are *very* similar. It is, therefore, reasonable to assume that, if the model line widths could be adjusted to the velocity dispersion used for the galaxy data, the Ca8498-color relations of the early-type galaxies and the Galactic bulge would not differ significantly. This problem is not evident in the other atomic line indices because the effect, while present, is not as pronounced for the other atomic lines measured here; the resulting change in slope of the other color-index relations is insufficient to produce significant deviations from the early-type galaxy trends.

Na I and I(8197)

Unfortunately, the other bulge/galaxy differences are not so easy to explain. Due to the velocity broadening of spectral features in the galaxy spectra, the Na I and I(8197) indices probably measure the same feature, so they will be discussed in tandem as the

Na/I(8197) feature. Note that the trends in these features which the Galactic bulge models predict are nearly perpendicular to the relations followed by the Virgo galaxy nuclei. Because the Na I doublet is strong in late-type dwarfs, it would be easy to jump to the conclusion that the increasing strength of the Na/I(8197) feature with increasing galaxy luminosity is caused by a changing initial mass function (IMF) in which more luminous galaxies have more dwarf-heavy IMFs. However, several factors must be considered in examining the Na/I(8197) feature:

- this feature lies in a region of the spectrum which is contaminated by a telluric H₂O band, whose absorption must be properly removed before the feature can be measured.
- Xu *et al.* (1989) have shown that the apparent Na/I(8197) feature in the spectra of giant elliptical galaxies also contains absorption from TiO and an atomic line blend.
- the narrowness of the bandpasses used to define the Na I index makes it very susceptible to noise fluctuations, wavelength calibration errors, etc. in the spectra.
- simulations involving bulge star spectra reveal that, even in light of the Xu *et al.* (1989) results, this is a very complex region of a composite spectrum. This is illustrated in Figures 67 - 69. In these figures, the bold solid line is a spectrum of the field S0 galaxy NGC 3115, and the three other spectra are, from bottom to top in the figures, an M giant, a CN-strong K giant (see Chapter 2),

and the sum of the K and M giant spectra, respectively. The vertical lines in Figure 69 are drawn at the central wavelengths of the continuum and feature bands used to measure the Na I (solid lines) and I(8197) (dotted lines) indices. Figures 67 and 69(a) show that, although the continuum slope is wrong, the general shape and many of the major spectral features of the galaxy spectrum are well-matched by the sum of the fluxes of the CN-strong K giant and an M2-4 giant; however, the Na/I(8197) feature is notably missing. In addition, it is apparent that CN absorption also affects the flux in the bandpasses used to measure the Na I and I(8197) indices. Figures 68 and 69(b) show that the presence of late-M giants and LPVs can seriously affect the blue continuum regions used to measure the Na/I(8197) feature, perhaps producing spurious feature strengths.

Overall, the complexity of this region of the spectrum begs the question: What do the Na I and I(8197) indices really measure? Can we attribute an increase in the strength of either index to any particular change in the stellar population? For example, Deslisle & Hardy (1992) also found that the Na I index was stronger in more luminous galaxies, and they attributed this to increasing metallicity. Is this reasonable? Figures 67 - 69 seem to indicate that spectral synthesis is the only way to discern what the Na/I(8197) feature truly represents and how to best interpret it.

Still, regardless of what these indices really measure, the fact that the Virgo galaxy nuclei follow different trends for Na I and I(8197) with color than the Galactic bulge models predict indicates that either: (1) there is some problem with modelling these

features, (2) the strengths of Na I and I(8197) do not vary monotonically with color and could possibly “bottom out” and begin to increase again with redder integrated colors, or (3) some parameter is varying differently in the stellar populations of the Virgo E/S0 nuclei and the Galactic bulge.

The first of these three factors is a serious possibility. A wavelength calibration error in a subset of the Galactic bulge star spectra has recently been discovered; since the majority of the stars used to define the red end of the I(8197), $(H - K)_0$ and Na I, $(H - K)_0$ calibration relations shown in Figures 36(e) and 38(a), respectively, are a part of this group, these calibration relations could be in error for the reddest giants. The possible effect of such an error can be inferred from a comparison of the Na I index strengths of the models of BW and the -8° field ; the -8° model has a stronger Na I index than the BW model because the *giants* in the -8° field, while bluer on average than the BW giants, have a greater overall Na I index. Unfortunately, a more thorough exploration of this situation will require a more complete set of Galactic bulge models and is left for future consideration.

TiO

The fact that the Virgo galaxy nuclei and the Galactic bulge TiO-color gradients differ is quite interesting and potentially crucial in determining if these two types of gradients are produced by the same stellar population variations. Since the I(7100) index does not show the same galaxy/bulge disagreement as the other TiO indices, it will be assumed in the following discussion that this is due to the fact that it

is improperly weighted in the modelling and would show the same pattern as the other TiO bands if properly computed. This needs to be checked because the I(7100) index is the strongest and best-determined TiO index and also shows the tightest correlations with color in the galaxy nuclei.

The $(J - K)_0$ color may be a universally good indicator of stellar effective temperature, probably because it is less sensitive to differential blanketing than other colors. For example, McWilliam & Rich (1994) have shown that BW and field K giants follow the same $(J - K)_0$, T_e relation. However, this may not be as true for M giants due to TiO absorption in the J band. In any case, since the light of normal, early-type galaxies is highly giant-dominated at infrared wavelengths, the $(J - K)_0$ color is probably a decent indicator of the average, luminosity-weighted temperature of the red giant branch. This temperature is mainly determined by the H^- opacity, which is dictated by the abundances of the major electron donors (Renzini 1977, Iben & Renzini 1984). Since iron is usually by far the major electron donor, $(J - K)_0$ should best track Fe abundance. On the other hand, the V -band light is susceptible to TiO blanketing, so the $(V - K)_0$ color of a stellar population should more closely follow the light element abundance trends. If these suppositions about the $(J - K)_0$ and $(V - K)_0$ colors hold, then what do the observed gradients tell us?

Assuming that the radial gradients in the Galactic bulge are best represented by the -8° model and the basic BW model, then the TiO, $(V - K)_0$ trend is the same within the bulge as it is between the early-type galaxy nuclei. This is consistent with $(V - K)_0$ tracking light element abundances. However, the TiO, $(J - K)_0$ gradients

differ in the bulge and the galaxies. In interpreting these differences, it is important to recall that the TiO , $(J - K)_0$ relations for the Virgo E/S0 galaxies were significant at less than 99% confidence (see Table 6). In other words, these two parameters may be totally uncorrelated, making the differences in slope less meaningful. If, instead, the slopes are taken at face-value, then the TiO , $(J - K)_0$ gradients are steeper in the Galactic bulge, and the model/galaxy comparison indicates that the $[\text{Ti}/\text{Fe}]$ ratio is varying substantially within the bulge but changing relatively little (or at least to a lesser extent) between galaxy nuclei of differing luminosity. This is in the opposite sense of the light element, iron abundance relationship implied from the optical line indices measured in early-type galaxies and discussed above. Is something unusual going on in the Galactic bulge? Unfortunately, a more extensive grid of models is needed to explore this further.

Table 38: A Comparison of Baade's Window Models

Component	K_0	% K Light	$(V - I)_0$	$(V - K)_0$	$(J - K)_0$	$(H - K)_0$	CO	H ₂ O
Basic BW Model								
M giants	3.577	51%	2.099	4.895	1.002	0.242	0.249	0.120
other stars	3.625	49%	0.987	2.412	0.584	0.072	...	...
total	2.848	100%	1.158	3.078	0.778	0.154	0.107	0.081
Terndrup <i>et al.</i> (1990) Model								
M giants	...	66%	...	4.96	1.06	0.29	...	...
other stars	...	34%	...	2.31	0.56	0.06	...	...
total	...	100%	...	3.32	0.86	0.21	...	...
Basic BW Model: M Giants = 66% at K								
M giants	2.905	66%	2.099	4.895	1.002	0.242	0.249	0.120
other stars	3.625	34%	0.987	2.412	0.584	0.072	...	...
total	2.454	100%	1.267	3.388	0.841	0.181	...	...

Table 39: A Comparison of the Virgo E/S0 Galaxy Trends and the Galactic Bulge Model Gradients

y	Virgo E/S0 Nuclei ^a		-8°, BW model C		-8°, BW model w	
	$\delta y/\delta x$	σ	$\delta y/\delta x$	$\Delta(\text{slope})^b$	$\delta y/\delta x$	$\Delta(\text{slope})^b$
$x = (V - K)_0$						
$(J - K)_0$	0.254	0.054	0.242	0.2 σ	0.228	0.5 σ
$(H - K)_0$	0.075	0.028	0.071	0.1 σ	0.101	0.9 σ
CO	0.145	0.028	0.099	1.6 σ	0.089	2.0 σ
H ₂ O	-0.014	0.045	0.123	3.0 σ	0.030	1.0 σ
I(7100)	0.103	0.011	0.082	1.9 σ	0.165	<u>5.6σ</u>
I(7450)	0.027	0.013	-0.003	2.3 σ	-0.017	<u>3.4σ</u>
I(7890)	0.046	0.016	0.082	2.3 σ	0.118	<u>4.5σ</u>
S(7890)	0.048	0.016	0.092	2.8 σ	0.135	<u>5.4σ</u>
I(8197)	0.066	0.014	0.000	<u>4.7σ</u>	0.004	<u>4.4σ</u>
I(8460)	0.022	0.016	0.061	2.4 σ	0.084	<u>3.9σ</u>
Na I	1.239	0.262	-0.61	<u>7.1σ</u>	-0.38	<u>6.2σ</u>
Mg8807	0.009	0.200	-0.03	0.2 σ	0.00	0.1 σ
Ca8498	0.728	0.437	-1.23	<u>4.5σ</u>	-0.76	<u>3.4σ</u>
Ca8542	0.214	0.465	-0.72	2.0 σ	-0.30	1.1 σ
Ca8662	-1.116	0.758	0.07	1.6 σ	0.00	1.5 σ
Ca II	-1.463	0.972	-0.65	0.8 σ	-0.34	1.2 σ
$x = (J - K)_0$						
$(H - K)_0$	0.283	0.073	0.296	0.2 σ	0.444	2.2 σ
CO	0.263	0.098	0.408	1.5 σ	0.389	1.3 σ
H ₂ O	-0.015	0.098	0.507	5.3 σ	0.130	1.5 σ
I(7100)	0.274	0.041	0.338	1.6 σ	0.722	<u>10.9σ</u>
I(7450)	0.051	0.042	-0.014	1.6 σ	-0.074	3.0 σ
I(7890)	0.078	0.044	0.338	<u>5.9σ</u>	0.519	<u>10.0σ</u>
S(7890)	0.088	0.043	0.380	<u>6.8σ</u>	0.593	<u>11.7σ</u>
I(8197)	0.171	0.039	0.000	<u>4.4σ</u>	0.019	<u>3.9σ</u>
I(8460)	0.058	0.048	0.254	<u>4.1σ</u>	0.370	<u>6.5σ</u>
Na I	3.903	0.784	-2.54	<u>8.2σ</u>	-1.67	<u>7.1σ</u>
Mg8807	0.439	0.522	-0.14	1.1 σ	0.00	0.8 σ
Ca8498	0.874	1.279	-5.07	<u>4.7σ</u>	-3.33	<u>3.3σ</u>
Ca8542	-1.442	1.093	-2.96	1.4 σ	-1.30	0.1 σ
Ca8662	-4.267	1.905	0.28	2.4 σ	0.00	2.2 σ
Ca II	-6.018	2.183	-2.67	1.5 σ	-1.48	2.1 σ

^asee Table 6

^bslopes are usually different at > 99% confidence if $\Delta(\text{slope}) > 3.0\sigma$;
for $y=\text{H}_2\text{O}$, $\Delta(\text{slope}) > 5.8\sigma$ applies.

Figure 60: The Baade's Window (BW) color-magnitude diagram. The photometry is reproduced from Figure 24. The dotted box encloses the stars included in the basic BW model (model C) described in Chapter 4; the solid box encloses the stars included in the revised model described in Section 5.1.2. Two giant branch ridge lines taken from Terndrup (1988) overlay the data - the redder line is the ridge line used in BW model w, while the bluer one represents a field at $l = 0^\circ$, $b = -10^\circ$. The vertical dashed line is the estimated color boundary between K and M giants in BW; the horizontal dashed line separates the Galactic bulge and field M giants (Sharples *et al.* 1990).

Figure 61: The gradients in the Galactic bulge photometry predicted by the models as a function of $(V-K)_0$. Circles represent Virgo elliptical galaxies, and triangles are Virgo lenticulars. The heavy solid lines are linear least-squares fits to the Virgo galaxy data (see Chapter 3); the dotted lines are the 99% confidence limits on the values of the dependent variable predicted by these relations. Open symbols are the galaxies NGC 4382 and NGC 4435, which have been excluded from the sample used to define the linear relations. The BW model results are represented by the symbols C and w; the $Z = 0.0084$, 8.0 Gyr model of the -8° field is shown as the numeral 8. The dashed lines show the gradients inferred from the models and have been extrapolated in $\log radius$ to simulate the integrated light of the Galactic bulge at $b = -1^\circ$; the estimated position of this field is represented by the digit 1.

Figure 62: The gradients in the Galactic bulge photometry predicted by the models as a function of $(J-K)_0$. All symbols and lines have the same meaning as in Figure 61.

Figure 63: The gradients in the Galactic bulge molecular band indices predicted by the models as a function of $(V-K)_0$. All symbols and lines have the same meaning as in Figure 61.

Figure 64: The gradients in the Galactic bulge molecular band indices predicted by the models as a function of $(J - K)_0$. All symbols and lines have the same meaning as in Figure 61.

Figure 65: The gradients in the Galactic bulge atomic line pseudo-equivalent widths predicted by the models as a function of $(V - K)_0$. All symbols and lines have the same meaning as in Figure 61.

Figure 66: The gradients in the Galactic bulge atomic line pseudo-equivalent widths predicted by the models as a function of $(J-K)_0$. All symbols and lines have the same meaning as in Figure 61.

Figure 67: Examination of the Na/I(8197) region of the spectrum I. From bottom to top, the lower three spectra are those of a Galactic bulge M2-4 giant (star 3-138), a CN-strong Galactic bulge K giant (star 3-147), and the sum of the M2-4 giant and K giant spectra. The heavy line is a spectrum of the field S0 galaxy NGC 3115.

Figure 68: Examination of the Na/I(8197) region of the spectrum II. From bottom to top, the lower three spectra are those of a Galactic bulge M7+ giant (star 3-138), a CN-strong Galactic bulge K giant (star 3-147), and the sum of the M7+ giant and K giant spectra. The heavy line is a spectrum of the field S0 galaxy NGC 3115.

Figure 69: Examination of the Na/I(8197) region of the spectrum III. (a) an enlargement of Figure 67 in the region of the Na I and I(8197) indices. (b) an enlargement of Figure 68 in the region of the Na I and I(8197) indices.

CHAPTER VI

CONCLUSIONS

This dissertation has presented an analysis and discussion of several aspects of the cool stellar populations of early-type galaxies. Red (6800 -9200 Å) and near-infrared (*K*-band) spectra were obtained for 17 E/S0 galaxies in the Virgo cluster, ten Coma cluster members and seven field galaxies. The strengths of the Ca II triplet at $\lambda\lambda 8498$, 8542 and 8662 Å, the Na I doublet at $\lambda\lambda 8183$ and 8195 Å, the Mg I $\lambda 8807$ Å line, and several molecular bands of TiO and VO were measured from the red spectra. Absorption due to the near-infrared CO band with bandhead at 2.29 μm was measured from the infrared spectra.

The behavior of the spectral indices was examined for the Virgo galaxy nuclei as functions of luminosity and color through linear least-squares fitting, and the following general trends were found:

- the features which varied significantly with luminosity also tended to show statistically significant correlations with color,
- the CO band is deeper in redder and brighter galaxies,
- the TiO bands strengthen with redder colors and higher luminosities,

- the VO band was not detected in any galaxy nucleus,
- the Na I doublet, which is unresolved in the spectra examined here, gets stronger with redder colors and higher luminosities, and
- the Mg I line and the Ca II triplet lines do not vary significantly among galaxies of different color or brightness.

Unfortunately, the spectra of the Coma galaxies were very noisy, and the Coma members, by themselves, showed no obvious trends with either color or luminosity. These E/S0 galaxies tended to lie near the linear relations defined by the Virgo galaxies, but they exhibited a much larger scatter than the Virgo galaxies did. A two-sample test for independent samples with unequal variances showed that the Coma galaxy data were consistent with the Virgo trends. No meaningful comparison could be made with the field galaxies because only four of the seven observed field galaxies had the necessary photometry to be included in the analysis.

Although early-type galaxies follow a color-magnitude relation and many also contain internal color gradients, it has never been convincingly shown whether the color changes within the galaxies are caused by the same stellar population variations producing the color changes along a luminosity sequence of galaxies. Unfortunately, the galaxy spectra collected here were not of sufficient quality to examine the radial dependence of the spectral features measured. However, since the integrated spectra of the bulges of spiral galaxies are very similar to those of E/S0 galaxies, it was assumed that the radial population changes within bulges are representative of those

within early-type galaxies. With this assumption in mind, models were constructed to represent the integrated light of the Galactic bulge as a function of radius.

Models were first constructed to represent Baade's Window (BW), a Galactic bulge field located at $b = -3.9^\circ$. From these models, the following conclusions were reached:

- the integrated light of Baade's Window is very similar to the integrated light of the nucleus of a low-luminosity early-type galaxy;
- the integrated light in BW is giant-dominated;
- the fluctuation magnitude of the stellar population used in the basic BW model is consistent with a distance to the Galactic bulge of 8 kpc;
- the stellar population in Baade's Window is quite complex - it either consists of a purely "bulge" population with a large spread in its properties (such as metallicity) or a mixture of separate populations, possibly halo and bulge;
- most, if not all, of the observed characteristics of the BW population which have usually been attributed to an overall increased metallicity in BW stars can be better explained by selective enrichment of Ti, CN and other light elements *without* a corresponding Fe enhancement; and
- the results of the BW model differ from the BW model of Terndrup *et al.* (1990), which resembled a much brighter elliptical galaxy; this appears to be due to the different relative contributions of the M giants to the integrated light of the respective models.

Next, models were built for Galactic bulge fields at $b = -6^\circ$ and $b = -8^\circ$. From the BW and -8° models, radial gradients were examined in the Galactic bulge and compared to the changes which occur along a luminosity sequence of early-type galaxies in the Virgo cluster. This comparison showed that:

- extrapolations of the derived radial gradients to the inner bulge indicate that the difference between the BW models and a bright E/S0 galaxy don't appear to be due only to the fact that BW represents a region of the Galactic bulge much further from the center of the galaxy than the spectra of the early-type galaxies sample;
- differences in the slopes of the Ca8498, color relationships in the Galactic bulge and in early-type galaxy nuclei can be attributed to the lack of velocity dispersion corrections in the bulge models;
- the Na I and I(8197) indices increase steeply with redder colors in the Virgo galaxies but appear to *decrease* with color in the Galactic bulge; this effect is not understood but may be caused by some deficiency in the modelling; and
- differences in the slopes of the TiO/color trends in E/S0 galaxies and in the Galactic bulge may indicate that the [Ti/Fe] ratio is changing differently in these two instances.

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