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THE STAR FORMATION HISTORY OF GALAXIES

by

Charles Tsun-Chu Liu

A Dissertation Submitted to the Faculty of the
DEPARTMENT OF ASTRONOMY
In Partial Fulfillment of the Requirements
For the Degree of
DOCTOR OF PHILOSOPHY
In the Graduate College
THE UNIVERSITY OF ARIZONA

1996
As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Charles Tsun-Chu Liu entitled The Star Formation History of Galaxies and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

Richard Green

Robert Kennicutt

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Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

Dissertation Director Richard Green
STATEMENT BY AUTHOR

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SIGNED: [Signature]
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Who gave me so much time, energy, support, love and attention.

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As we've whiled our hours away, warbling all these years,
I know I've learned a lot - and I think we've pleased a lot of ears.

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“I don’t know much, but I know I love you,“ as the lyrics go;
“And that may be all I need to know.”

And lastly, thank YOU, dear reader; you may cringe at my verse,
But believe me: in prose, it would have been worse.
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The star formation history of galaxies is the primary influence on galaxy evolution, and hence the evolution of almost all the visible matter in the universe. In this dissertation, I present studies of the star formation history of galaxies which have come from two distinct perspectives: the study of galaxies that have unusual star formation histories, and the search within the general galaxy population for galaxies with unusual star formation histories.

A spectrophotometric atlas of 40 merging and strongly interacting galaxies is obtained and analyzed in order to examine their stellar populations and star formation histories. Within the sample, the subsample of 10 ultraluminous IRAS systems is compared with the optically selected subsample. The population of objects in the sample with anomalously strong Balmer absorption lines, a spectral signature indicative of post-starburst evolution, is examined and compared with distant "E+A galaxies" which have similar spectrophotometric properties.

Spectrophotometry across the entire optical wavelength range is obtained and analyzed for a sample of 8 E+A galaxies, ranging in redshift from $0.09 \leq z \leq 0.54$. The method of stellar population modeling, widely used with only minor variations in the astronomical community, is examined and its strengths and limitations are discussed.

A deep, broad-band multicolor galaxy survey is assembled and analyzed for information about the star formation evolution of the field galaxy population. A technique is developed to identify the redshifts and spectral types of the survey galaxies using the very low-resolution spectrophotometry provided by the multicolor data. The red galaxy population is examined for signs of active star
formation evolution. The blue galaxy population is analyzed using number counts and luminosity functions subdivided by redshift. The two major results are: (1) The U-band selected blue galaxy luminosity function in the redshift range $0.02 \leq z < 0.15$ is very steep and very similar to that of local Magellanic spiral and irregular galaxies. (2) An excess population of starburst galaxies is observed at $z \geq 0.3$ which is not observed at $z < 0.3$. These galaxies may contribute significantly to the observed luminosity function evolution at $z \geq 0.3$, and then fade and redden at lower redshifts.
CHAPTER 1

INTRODUCTION

1.1. Motivation

The star formation history of galaxies essentially dictates the evolution of galaxies, and hence the evolution of almost all the visible matter in the universe. Clearly, then, the study of the star formation history of galaxies all but motivates itself. The subject encompasses a vast and grand scale, from the behavior of gas in individual molecular clouds to the systematic evolution of the entire galaxy population since the beginning of cosmic time. With this dissertation, I hope to contribute to our understanding of this inspiring and challenging scientific problem.

1.2. Background

To approach the star formation history of galaxies at its most basic level is to look at the star formation history of a single galaxy. Three very general scenarios for star formation can occur in any given galaxy: (1) an initial burst of star formation when the galaxy is first formed; (2) some level of continuous, perhaps slowly
declining, star formation which has gone on since the time of formation; and (3) an episode of star formation which occurs some time after the formation epoch, and lasts only a short time compared to the lifetime of the galaxy. If the star formation rate is intense during this episode, it is commonly called a starburst. For any galaxy, the interplay between these three processes determines its star formation history.

Historically, the generally accepted paradigm for relating these star formation scenarios to the observed galaxy population is a simple one: most early-type, i.e. elliptical and lenticular galaxies, had essentially all their star formation completed during the initial burst, while most late-type, i.e. spiral galaxies, have undergone varying levels of continuous star formation since they were formed. The contribution of starbursts in galaxies' star formation histories has been recognized for some time as well — for example, by Rieke & Lebofsky (1978) for spiral galaxy nuclei, and Larson & Tinsley (1978) in interacting galaxies — and is now understood to be a dominant process in any active evolution of the star formation rates of galaxies.

1.3. The Layout of This Work

When star formation evolution occurs in the galaxy population, it manifests itself in several basic ways. One way is that individual galaxies will exhibit unusual star formation activity — ongoing starbursts, for example, or the fading remnants of recently ended ones. Another way is that galaxies as an ensemble will show different star formation properties at different epochs — perhaps the galaxy population was more luminous or had bluer broad-band colors on the average, or contained a larger fraction of starbursting galaxies. In this dissertation, I seek insight into
the star formation history of galaxies through studies from these two distinct and complementary directions.

1.3.1. Merging, Strongly Interacting and E+A Galaxies

First, I examine the star formation histories and properties of two kinds of galaxy systems that are rapidly evolving: merging and strongly interacting galaxies, which are in the process of large-scale dynamical evolution, and poststarburst (or “E+A”) galaxies, which have had starburst activity in their recent histories. Galaxy mergers and interactions are among the most visually dramatic events in the universe; E+A galaxies are spectroscopic signposts that mark the recent occurrence of strong starburst activity. The effects of the interaction process on the star formation histories of the galaxies concerned are well documented (see Bushouse 1986 and references therein; Hibbard 1995 and references therein). The use of E+A galaxies as diagnostics to test the star formation histories of galaxy populations, particularly in distant rich clusters of galaxies, has also been explored (e.g., Couch & Sharples 1987; Barger et al. 1996). However, the spectrophotometric properties of merging and strongly interacting systems as a class of objects, and E+A galaxies as a class of objects, had not yet been studied. This oversight had to be addressed; how, after all, can the merger process and the E+A phenomenon be used as tools to study the star formation history of galaxies if mergers and E+A’s themselves are not understood as a population?

In collaborations with Robert Kennicutt (University of Arizona) and Richard Green (National Optical Astronomy Observatories), I obtain spectrophotometric surveys of 40 merging and strongly interacting galaxy systems, and 8 E+A galaxies identified in the literature. Then, I examine the spectrophotometric properties of the galaxies in the merger survey, with particular emphasis on their
current star formation rates, their far infrared luminosities, and their relationship to high-redshift E+A galaxies. With the E+A galaxies, I model their stellar populations to study the starburst activity that has occurred within them. I also test the effectiveness of the modeling procedure used not only by me but by almost everyone else in the community.

1.3.2. Star Formation In The Field Galaxy Population

Second, I examine the star formation history of the field galaxy population as a whole. The goal of such a study is to see how the star formation properties of galaxies have evolved as the universe has aged, and to quantify the nature and amplitude of such evolution. The basic requirement of such a study is a large sample of galaxies obtained in a well-defined way; for the studies in this dissertation, I use a deep, multicolor CCD field survey (Hall et al. 1996) obtained by Richard Green and Patrick Osmer (Ohio State University) and reduced, calibrated and catalogued by Patrick Hall (University of Arizona).

The other key ingredient to the study of field galaxy evolution is the look-back times, and hence their ages relative to the present epoch, of the galaxies in the sample. This quantity is obtained for each galaxy by measuring its redshift. In this dissertation, I design and test a technique to estimate the redshifts and spectoscopic Hubble types of the galaxies in the sample using broad-band, optical multicolor photometry, rather than resorting to costly and time-consuming spectroscopy. I then search for star formation evolution in galaxies with early-type galaxy colors by looking at their near-ultraviolet fluxes. Finally, I quantify the evolution of galaxies with late-type galaxy colors by constructing their luminosity functions in various redshift ranges, and try to identify any particular sub-populations of galaxies that would be significant contributors to star formation evolution.
CHAPTER 2

PRESENT STUDY

The studies of the star formation history of galaxies that comprise this dissertation are presented in the form of six papers. The main results of each paper are summarized below.

2.1. Appendix A:

A Spectrophotometric Survey of Merging Galaxies

We present longslit spectrophotometry of 40 merging or strongly interacting galaxy systems in the wavelength range 3650-7100 Å. Along with optically selected objects, the sample includes 10 ultraluminous IRAS galaxies with evidence of ongoing merger activity. The data show a wide variety of phenomena, with spectra resembling those of isolated elliptical galaxies, early and late-type spirals, AGN, starbursts and post-starburst systems.

2.2. Appendix B:
Spectrophotometric Properties of Merging Galaxies

We present quantitative analysis of longslit spectrophotometry of 40 merging and strongly interacting galaxy systems, in the wavelength range 3650-7100 Å. Along with optically selected objects, the sample includes 10 ultraluminous IRAS galaxies with ongoing merger activity. The mergers exhibit a very large range of spectral properties, ranging from completely evolved stellar populations to emission-line dominated starbursts and absorption-line dominated post-starburst systems. The spectral types are correlated with the morphological types of the merging galaxies, as best as they can be inferred.

The sample has much higher mean star formation rates than isolated galaxies, as measured by Hα+[NII] line emission. The distribution of [OII] equivalent widths in the sample is very different from that of local field galaxies, but does resemble the EW([OII]) distribution for faint blue field galaxies studied in deep redshift surveys. The far-infrared (FIR) luminosities and L(FIR)/L(B) ratios of the optically selected subsample are substantially higher than that of field galaxies as a whole. The ultraluminous IRAS mergers have distinctly higher L(FIR) and L(FIR)/L(B), but are similar to the optically-selected mergers at optical wavelengths; on the average, their optical continuum colors are actually somewhat bluer than the optical subsample, indicating the presence of a global, young stellar population along with heavily dust-enshrouded nuclei. The frequency of the appearance of Seyfert nuclei and LINERs in the sample is also discussed.

A considerable fraction of the mergers exhibit spectra with anomalously strong Balmer absorption, when compared to nearby normal galaxies. Many of these systems have spectra resembling those of distant “E+A” galaxies. A quantitative comparison of the Balmer absorption-dominated mergers with several E+A galaxies
at high redshift shows that they are indeed similar, and suggests that the two kinds of galaxies may be the same class of objects.

2.3. Appendix C:
Spectrophotometry and Stellar Population Models of “E+A” Galaxies

We present longslit spectrophotometry of eight “E+A” galaxies which have been previously identified in the literature. We use a simple two-parameter modeling scheme to test if their stellar populations can be characterized uniquely by a decaying instantaneous starburst of well-determined age superposed upon a steady-state galaxy substrate. Five of the objects are well characterized by burst-plus-elliptical galaxy models; two others are best fit by burst-plus-spiral galaxy models. One object cannot be described by such models, but does resemble the spectra of some nearby merging galaxies with E+A-like spectra, possibly suggesting a multiple-burst scenario. Significant degeneracies, however, combined with the finite signal-to-noise of the data, severely limit the effectiveness of using optical spectral energy distributions alone to constrain the ages and mass fractions of the starburst components. The interpretation of E+A galaxies, especially at high redshift, must be approached cautiously.

2.4. Appendix D:
An Optical Multicolor System For Measuring
Galaxy Redshifts And Spectral Types

A method of obtaining approximate redshifts and spectroscopic Hubble types of galaxies using a photometric system of six broad-bandpass filters is developed. In an evaluation of its accuracy using two distinct galaxy samples, the photometric redshifts are found to have an absolute mean deviation of ±0.05 from spectroscopically determined redshifts. Possible systematic errors of the method are investigated, including the effects of post-starburst ("E+A") galaxies and attempts to measure redshifts with incomplete color information. Applications of the technique are discussed.

2.5. Appendix E:
A Search For Star Formation Evolution In Early-Type Galaxies

We apply a color-selection criterion to extract red galaxy candidates from the deep multi-color survey of Hall et al. (1996). We select the galaxies using red colors (V-R-I86 and R-I75-I86), then compare their bluer colors (B-R and V-R respectively) to color evolution models of non-evolving and passively evolving elliptical galaxy templates. Thus, we attempt to measure directly the excess of rest-frame ultraviolet colors in these galaxies, as an indication of their star formation evolution as a function of redshift. We see suggestions of ultraviolet excess which are inconsistent with no-evolution or passive evolution in the selected red galaxy population, and require at least some increase in the massive star formation rate since z~0.8. However, the errors in the photometry are sufficiently high at the apparent magnitudes of interest (R_\text{app} \leq 21.5) that our result is not
statistically significant. We discuss the improvements to the dataset that would be required to confirm our results at a robust statistical level. Specifically, an increase of approximately 1.5 magnitudes in the B limiting depth of the sample, and 0.7 magnitudes in the V and R limiting depths, would be sufficient to achieve the desired scientific goal.

2.6. Appendix F:
Luminosity Functions and Number Counts of Blue Galaxies
In A Deep Multicolor CCD Field Survey

A complete sample of 651 field galaxies with 17.0 < U ≤ 21.1, each with U-B-V-R-I7500-I8600 photometry, has been selected from a deep field survey which covers 0.83 deg² along six lines of sight. Each galaxy's spectroscopic Hubble type and redshift has been measured using the photometric techniques developed by Liu (1996). Of these, the 560 galaxies classified as spectral type Sbc or bluer are analyzed for signs of evolution with redshift, and for unusual star formation histories. Total number counts of the blue galaxies in the U-band give a count slope d(logN)/dM≈0.55, consistent with previous studies. In the redshift range 0.3 ≤ z ≤ 0.5, the slope steepens sharply to 0.9, indicating strong luminosity and/or number density evolution at that epoch.

The luminosity function at 0.02 < z < 0.15 has a very steep α ≈ -1.9 down to M(B)≈-14. This is consistent with the measurement of Marzke et al. (1994) for Magellanic spirals and irregulars, suggesting that this U-limited sample is strongly influenced by galaxies which have the spectrophotometric or surface-brightness properties of morphologically selected Sm-Im galaxies. The luminosity functions at 0.15 ≤ z < 0.3 and 0.3 ≤ z ≤ 0.5 are consistent with a faint-end slope α ≈ -1.5, as found
by Ellis et al. (1996), and show significant brightening of $M^*$ as found by Lilly et al. (1995).

A significant population of very blue (rest frame $U-R<0.3$) galaxies, with spectral energy distributions indicating strong starburst activity, is observed at $z\geq0.3$ but not at $z<0.3$. These may be galaxies temporarily brightened by global starbursts, which subsequently fade and redden at lower redshifts.
REFERENCES


Liu, C. T. 1996, this work, Appendix D.


This manuscript was prepared with the AAS LaTeX macros v4.0.
APPENDIX A

A SPECTROPHOTOMETRIC ATLAS OF MERGING GALAXIES

November 15, 1996

To Whom It May Concern,

This letter regards the following three published works:


As the lead author for each of these three papers, I hereby exercise my copyright and allow them to be published in my dissertation. For any further clarification, please contact the Astrophysical Journal Office in Tucson, Arizona at (520) 318-8000.

Sincerely,

Charles T. Liu
A SPECTROPHOTOMETRIC SURVEY OF MERGING GALAXIES

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Received 1994 November 22; accepted 1995 March 20

ABSTRACT

We present long-slit spectrophotometry of 40 merging or strongly interacting galaxy systems in the wavelength range 3630–7100 Å. Along with optically selected objects, the sample includes 10 ultraluminous IRAS galaxies with evidence of ongoing merger activity. The data show a wide variety of phenomena, with spectra resembling those of isolated elliptical galaxies, early and late-type spiral galaxies, active galactic nuclei starbursts, and post-starburst systems.

Subject headings: galaxies: interactions — galaxies: stellar content — infrared: galaxies—surveys

1. INTRODUCTION

Galaxy mergers have become an increasingly important area of study, figuring prominently in a wide range of observed phenomena. Since the seminal theoretical work of Toomre & Toomre (1972) and the observational work of Larson & Tinsley (1978), a steadily growing body of evidence indicates that galaxy interactions can affect almost every aspect of galaxy evolution. In a merger event, where the interaction is particularly strong, one might expect the interaction phenomena to be even more pronounced. Furthermore, the creation of a single galaxy from two original galaxies, if prevalent, would have a direct impact on galaxy number counts, luminosity functions, and the evolution of clusters of galaxies and large-scale structure. Clearly, an understanding of the stellar populations, star formation, and nuclear activity in mergers is needed to answer a number of important astrophysical problems.

Surprisingly, very little hard data exist on the spectrophotometric properties of mergers as a class to answer many fundamental questions about merging galaxy systems. For example, nuclear spectra of some mergers are available from the literature (e.g., Keel et al. 1985; Sanders et al. 1988; Sekiguchi & Woltzecroft 1993; Kim et al. 1995; Veilleux et al. 1995), but most of these data do not show the spatial extent of star formation. We thus cannot tell how the global star formation properties of mergers compare with their nuclear activity. Detailed studies of individual mergers (e.g., Schweizer 1982; Hamilton & Keel 1987; Hippelein 1989; Stanford & Balcells 1990; Neff et al. 1990; Bernhofer 1993; Petrosian & Burenkov 1993) and purely integrated spectra of mergers (e.g., Kennicutt 1992) are enlightening but few in number. The frequency of active galactic nuclei (AGNs) and QSOs in mergers is also still uncertain; some enhancements in activity have been seen in interacting and close-companion galaxy systems (Dahari 1984, 1985; Cutri & MacAlary 1985; Keel et al. 1985; MacKenty 1989; Veilleux et al. 1995), whereas Bushouse (1986) saw a deficiency of AGNs in closely interacting disk systems, but it has not yet been shown how nuclear activity is distributed among mergers in general. Finally, study of the so-called "poststarburst" or "E+A" galaxies (Dressler & Gunn 1982; Lavery & Henry 1988; Oegerle, Hill, & Hoessel 1991) has linked their creation with merger activity; it is unknown whether merger events commonly produce starbursts and/or postburst "E+A" systems or do so only occasionally.

To address these and other issues regarding mergers, we have undertaken a comprehensive spectrophotometric survey of merging galaxies. Using high-resolution (4–8 Å), long-slit spectroscopy, we have obtained data on a sample of 40 merging and strongly interacting galaxy systems. These data have been used to investigate questions about the rates, timescales, and spatial distributions of ongoing star formation, and the occurrence of starbursts, post-starbursts, and AGN phenomena in mergers (Liu & Kennicutt 1995). This paper presents the spectrophotometric data and describes the spectral properties of individual objects.

2. SAMPLE SELECTION AND OBSERVATIONS

2.1. Sample Selection

Our sample was selected primarily in two ways. The bulk of the sample (28 galaxy systems) is an optically selected set of mergers from the Arp (1966) Atlas of Peculiar Galaxies, after the criteria established by Heckman (1983). These mergers were selected visually, and all exhibit severely distorted morphologies indicated by tidal structures, very peculiar galaxy shapes, and superpositions of all or part of the galaxy bodies. Unlike Heckman (1983), however, this sample was chosen without regard to the morphological type of the galaxies participating in the merger; thus, mergers of elliptical galaxies as well as spiral galaxies were included. Two of the objects, 3C 293 and 3C 305, are radio-selected galaxies with marked morphological distortions indicative of recent merger activity (Heckman et al. 1986).

The remainder of the sample consists of the 10 most infrared-luminous galaxies in the local universe, as measured by Soifer et al. (1987) in the IRAS Bright Galaxy Survey. As shown by Sanders et al. (1988), all 10 of these galaxies are strongly interacting or merging systems, also with very distorted morphologies. Spectroscopy of these objects in the red (specifically on and near Hα) shows evidence that they all have active nuclei: Seyfert types 1 and 2, low-ionization nuclear emission-line regions (LINERS), and H II nuclei. These galax-
ies have an average redshift of about 0.05 and represent the most distant members of the sample. Interestingly, a large number of the optically selected galaxies (eight out of 28) also belong to the IRAS Bright Galaxy Survey; this fact is accentuated because the optically selected sample was chosen completely independent of infrared luminosity. The infrared properties of the optically selected sample are discussed further in Liu & Kennicutt (1995).

It should be stressed that we use the term "merging galaxy" primarily as an observational definition rather than an interpretive one. Our targets exhibit the characteristics of galaxies that either have merged or are merging; in some cases, however, it is very difficult to be certain, based on morphological evidence alone, that the component galaxies are in fact merging. We do not exclude the possibility that the sample may contain projected pairs of galaxies that only appear to be mergers. Also, a few of our galaxy pairs (e.g., NGC 5257/5258) have relatively wide (~51 galaxy diameter) projected separations. For the purposes of this survey, we operationally define a "merger" as a system that appears to be in an advanced stage of the merging process, based on the selection criteria described above. The presence of large tidal structures, distorted morphologies, physical superpositions, and similar recessional velocities of the component galaxies in our objects increase our confidence that we have indeed selected truly merging galaxy systems.

2.2. Observations

Most of the spectrophotometry of the merging galaxy sample was obtained using the Boller & Chivens spectrograph with a TI 800 x 800 CCD, on the Steward Observatory 90 inch (2.3 m) telescope on Kitt Peak. These observations were made during a total of seven nights in the period from 1990 November to 1991 October. A long-slit aperture of 25 x 4' was used. The mergers in the sample were measured in the wavelength range 3650-7100 Å with a 600 lines mm\(^{-1}\) grating for 4 Å resolution; 17 mergers were also measured from 4850-7100 Å with a 7 Å resolution, using a 400 lines mm\(^{-1}\) grating.

The remainder of the sample, primarily the fainter objects, was measured in a series of observing runs from 1991 March to 1993 June with the Red Channel Spectrograph on the Multiple Mirror Telescope on Mount Hopkins. These observations covered the wavelength range 3650-6000 Å or 4600-7500 Å with approximately 9 Å resolution, using a 125 slit and a 300 lines mm\(^{-1}\) grating. One object, NGC 3921, was observed in 1994 March with the Blue Channel Spectrograph on the MMT, using a 500 lines mm\(^{-1}\) grating, from 3650-7100 Å with a 5 Å resolution. A complete list of observations and data is given in Table 1.

For each observation, the spectrograph slit was placed on the sky to cover as much of the merger system, including the nucleus, as possible. Where two distinct nuclei or progenitor galaxies were visible, both galaxies and nuclei were placed on the slit. A number of observations were also made with the galaxy trailed across the slit during the integration; these "drift-scanned" observations, previously used successfully by Kennicutt (1993), provided integrated spectra of those entire galaxies, to serve as comparison data for the fixed-long-slit spectra and for integrated galaxy spectra from the literature.

Standard data reduction techniques were used to process the data, primarily with the CCDRED and LONGSLIT packages in the IRAF software system. Errors in the spectrophotometry were dominated by sky subtraction and by uncertainties in the calibration, as evidenced by the variations in measured standard star fluxes. Some of the data were obtained on nights that were not photometric, and typical residuals from the mean calibration of the standard stars were 3%-7% on some nights. (Standards taken on photometric nights showed much lower residuals of 1%-2%.) The galaxy spectra, especially those trailed across the slit, are probably consistent to a precision better than the standards because they are extended objects rather than point sources. High-sky lines also caused some problems: the CCD detectors in the 90 inch Boller & Chivens Spectrograph and the MMT Red Channel have small irregularities in their flatness, which create variations in the point-source function along the slit (see Kennicutt 1992). Sky subtraction near bright sky lines was thus imprecise. In a few cases, a spectral feature in the observed galaxy was redshifted onto or near bright sky lines, particularly in the red (>5000 Å) spectra, making flux and equivalent width measurements difficult. Fortunately, the vast majority of sky lines fell far away from important spectral features, and the effects of imperfect night-sky line subtractions are essentially negligible.

The other significant contributor to spectrophotometric errors is the effect of wavelength-dependent atmospheric seeing and extinction, in those observations where the spectrograph slit was not oriented along the parallactic angle. We estimate this error to be small (<10%) for the majority of the data with two exceptions: for the untrailed spectra, NGC 7285/7284 and IRAS 05189-2524 were observed with the spectrograph slit aligned more than 30° away from the parallactic angle and at air masses high enough that the differential refraction between 3650 and 7000 Å was comparable to the slit width. In general, the nuclear apertures are affected most by the differential refraction; comparison with data from the literature (see below), however, seems to show that the effect is not serious.

Splicing the red and blue parts into a single galaxy spectrum may have contributed some error as well, but this is likely to be small, as there were always several hundred angstroms of continuum overlapping to get an accurate overlay. Overall, the energy distributions have uncertainties of ~5% in narrow wavelength ranges, up to a maximum of about 10%-15% peak-to-peak over broad wavelength ranges. The averaged rms deviations across each entire spectrum are about one-half or one-third of this value.

We were able to compare some of our data directly to those of Sanders et al. (1988), Kim et al. (1995), and Veilleux et al. (1995), who have published nuclear spectra of 18 objects in our sample. Their spectral coverage does not extend bluerward of 4000-4500 Å depending on the object; however, there is good qualitative agreement between the two data sets in the red portion of the spectrum, in terms of spectral shapes and general characteristics. Our measurements of observed emission-line flux ratios also agree well with theirs; the variation is ±10% in the [O III] /H\ beta, [N II] /H\ alpha, and [S II] /H\ alpha line ratios for spectra where the nuclear apertures are about the same size. The emission-line properties of our merger sample are discussed in detail in Liu & Kennicutt (1995).
### Table 1

**Galaxy Sample**

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<th>decl. (1950)</th>
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<th>Exposure (Red)</th>
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**Note:** Col. (4): c is kilometers per second; col. (5): integration time in seconds of the blue portion (3600-3600 Å) of the spectrum (SD = Steward Observatory 2.3 m; MMT = Multiple Mirror Telescope) col. (6) same as col. (3), but for the red portion (3000-7000 Å) of the spectrum. The asterisk (*) denotes that the components of NGC 5237/5238 have a projected nuclear separation of ~29 kpc, twice as large as the next largest separation in the sample.

### 3. Spectral Characteristics

The spectra of all the galaxies in the sample are presented below in Figures 1-16. The spectra plot wavelengths in angstroms versus flux in units of 10^-19 ergs cm^-2 s^-1 Å^-1.

We present two or more spectra of most of the galaxy systems: the whole-aperture spectrum of each merger and their individual nuclear spectra. The whole-aperture spectra were obtained by summing all the light from the galaxy into a single one-dimensional spectrum. In several cases, an integrated (trailing) spectrum has been substituted for the fixed whole-aperture spectrum.

The nuclear aperture of each merger system was centered at the peak in the optical surface brightness of the system. For galaxies with double nuclei, we labeled the brighter one “Nucleus 1” and the fainter one “Nucleus 2.” The nuclear regions...
Fig. 1—(Left) Spectra of NGC 750/751. There is no discernible difference in spectral characteristics between the whole and nuclear apertures. Flux is labeled in units of $10^{-13}$ ergs ~$^{-1}$ cm$^{-2}$ s $^{-1}$ Å$^{-1}$. (Right) Spectra of Arp 310, NGC 545/547, and NGC 7727. As with NGC 750/751, their nuclear spectra are also indistinguishable from the whole-aperture spectra presented here.
FIG. 2.—(Left) Spectra of NGC 7285/7284; (right) spectra of NGC 1888/1889.
Fig. 4. — (Left) Spectra of NGC 4676; (right) spectra of NGC 6621/6622
Fig. 5.—(Left) Spectra of NGC 3303; (right) spectra of Arp 195
Fig. 6. (Left) Spectra of NGC 3656; (right) spectra of NGC 2623
Fig. 7.—(Left) Spectra of NGC 520; (right) spectra of NGC 7252
Fig. 8.—(Left) Spectra of NGC 3921 and NGC 4038/4039; (right) spectra of NGC 5278/5279.
Fig. 9.—(Left) Spectra of NGC 3509; (right) spectra of NGC 5257/5258.
The nuclear spectrum of NGC 3448 is essentially indistinguishable from the whole-aperture spectrum presented here.
Fig. 13. (Left) Whole-aperture spectra of 3C 293, 3C 305, and Markarian 273; (right) their corresponding nuclear spectra.
Fig. 14. — (Left) Whole-aperture spectra of Markarian 231, IRAS 08532 + 3915, and IRAS 22491 - 1808; (right) their corresponding nuclear spectra.
Fig. 16. — (Left) Whole-aperture spectra of IRAS 05189 - 2524, UGC 5101, and Arp 220. (right) their corresponding nuclear spectra.
were defined to have fixed linear sizes of 1, 2, 4, or 6 kpc in diameter, for more straightforward comparison from one galaxy to another. (For linear size measurements we adopt \( H_0 = 82 \text{ km s}^{-1} \text{ Mpc}^{-1} \), to be consistent with an \( IRAS \)-luminosity \( \S \) formula used by Rieke & Lebédsky 1986 and Liu & Kennicutt 1995.) There were two main reasons for the different linear size apertures: the amount of spilled light along the spatial axis of the spectrograph slit and variations in atmospheric seeing variations from night to night. The linear sizes chosen are our best estimate of an accurate sampling of the flux from each nuclear region.

In the other spatial dimension, the size of the aperture was determined by the width of the spectrograph slit. This meant that the widths of the apertures varied from 0.2 to 3.5 kpc. Thus, each nuclear spectrum has been extracted from a rectangular aperture. Depending on the distance of the target, varying amounts of the areas surrounding the nuclei (e.g., bulge, disk, or circumnuclear gas) are also included; for a few objects, this may affect the observed emission-line properties (see Veilleux et al. 1995). However, since the apertures are small in any case, these spectra should represent the true emission from the galaxy nuclei with high accuracy. Table 2 lists the sizes and orientations of the various apertures.

3.1. The Optically Selected Subsample

Even a cursory glance shows that these galaxies exhibit a wide variety of spectral characteristics. The spectra of the optically selected portion of the sample can be very roughly divided into groups with similar spectral features; there is a continuous range of observed properties, however, so the organization of these galaxies is somewhat arbitrary. We present the groups roughly in order of increasingly blue continuum colors, as follows.

Figures 1–2.—These mergers have evolved or very slightly active stellar populations. NGC 750/751, Arp 319, NGC 545/547, and NGC 7727 are well-merged systems of elliptical or spheroidal galaxies. Despite apparently deep intermixing of their galactic material, and evidence of tidal tails and distortions, no effect on their combined or nuclear spectra is apparent. Their spectra look like those of undisturbed spheroidal galaxies. NGC 7284/7285 and NGC 1888/1889 are mergers whose original merging participants can no longer be unambiguously distinguished. (It is possible to discern a double nucleus in NGC 3656.) Their spectra show hints of an active stellar component, but we do not expect it to have any emission lines such as H\( \alpha \) or [N II].

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<td>NGC 7252</td>
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Note.—Col. (2): Position angle of the spectrograph slit. ° is N-S, 45° is NW-SE, and 90° is E-W. Col. (3): Aperture sizes are estimated; the first dimension is the length along the spatial direction of the spectrograph slit, the second is the width of the slit. Col. (5): Location of secondary nuclei in a system, expressed as the angular separation and direction along the spectrograph slit from the primary nucleus. Integrated spectra: apertures are E-W by N-S.

Figures 6–8.—These mergers have spectra characteristic of so-called poststarburst galaxies. NGC 3656, NGC 2623, NGC 520, NGC 3921, NGC 3921, and NGC 7252 are evolved mergers whose original merging participants can no longer be unambiguously distinguished. Their spectra show hints of an...
older, evolved population, but superposed upon that signature are very strong Balmer absorption lines, indicative of a significant B and A star population. Weak line emission is visible in the cores of the Hδ and Hγ line profiles. Weak to moderate [O ii] (EW = 6–12 Å) and Hα (EW = 9–31 Å) emission is apparent, and occasionally [O iii] is as well. These mergers are perhaps the results of massive starbursts which occurred sometime in the recent past (10^8–10^9 yr ago) and has since ended or greatly faded in intensity.

The blue portions of these galaxies, especially those of the integrated spectra, resemble the spectra of "E+A" galaxies seen at high redshift (Dressler & Gunn 1983; Lavery & Henry 1988), "E+A" galaxies are also believed to be poststarburst objects, possibly caused by mergers and interactions. Previous observations of "E+A" galaxies have not shown strong [O ii] or [O iii] emission, but a slight degradation in resolution, combined with the blurring of detail encountered with integrated spectra, can easily account for the moderate-to-weak oxygen forbidden lines not being observed. This effect is apparent in the integrated spectra of NGC 2623, NGC 520, and NGC 7252. The connection between these mergers and "E+A" galaxies is examined further in Liu & Kennicutt (1995) and Liu & Green (1995).

Figures 9–10.—These blue-continuum galaxies (NGC 4038/4039, NGC 5278/5279, NGC 3509, NGC 5257/5258, Arp 241, Arp 193) have strong Balmer emission lines and [O ii] indicating large amounts of star formation. Some of these systems also probably contain active nuclei, which would further augment their emission-line strengths. Their spectra resemble those of late-type spiral galaxies and some Magellanic irregulars (see Kennicutt 1992); indeed, most of these systems are in fact mergers of disk galaxies. NGC 3509 is an interesting case: one nucleus is typical of an Sb-type galaxy, while the other contains a nuclear starburst. Arp 193 also has two very different nuclei: one is strongly star forming, while the other (possibly a subnuclear knot of emission) has a deep Balmer absorption spectrum similar to the poststarburst objects described above.

Figures 11–12.—Arp 238, NGC 3448, NGC 4194, NGC 1614, and NGC 1222 are examples of starburst or H ii galaxies. Their spectrum is dominated by very strong emission lines and very blue continuum of young, massive stars and their H ii regions. The starbursts are primarily nuclear, as can be seen from their nuclear spectra. NGC 1614, however, has a small subnucleus that is just spatially resolved; its spectrum is again reminiscent of a postburst, Balmer absorption profile with some line emission.

3.2. The Radio and Infrared-Selected Subsample

The two radio sources 3C 293 and 3C 305 were identified by Heckman et al. (1986) to be merging systems with severely distorted optical morphologies and were included in our sample as comparison objects. Their optical spectra (Fig. 13) show them to have AGN-like nuclei, which is not surprising.

The IRAS-selected subsample all have far-infrared luminosities exceeding 10^12 L_⊙ in the energy regime of 8-1000 Å (Sanders et al. 1988; Kim et al. 1995). Optical imaging shows them to be merger systems as well, with the typical tidal tails and distorted morphologies. Their infrared luminosities exceed any of the other mergers in the sample by at least a factor of 2. How do their optical spectra compare to the optically selected galaxies?

Figures 12–14.—Markarian 231 and 273 have strong Seyfert nuclei. The high percentage of AGN in this ultraluminous IRAS sample supports the hypothesis (Sanders et al. 1988) that the dust-enshrouded nuclei of deep mergers may be the birthplace of QSOs.

Figures 14–15.—Galaxies IRAS 08572–3915, 22491–1808, 12112+0305, 14348–1447 and 15250+3609 resemble the blue-continuum, strong emission-line mergers of Figures 8–10. They exhibit low-ionization (LINER) and H II-type nuclear spectra.

Figure 16.—IRAS 05189–2524, UGC 5101 and Arp 220, like the other IRAS-selected mergers, have strong line emission, suggesting nuclear activity and/or high star formation rates. These objects are interesting in that their Balmer absorption features are also particularly strong. (The fixed-slit spectrum for Arp 220 does not extend blueward of 4400 Å, but the integrated spectrum clearly shows the Balmer absorption.) It seems that, outside their nuclear regions, these mergers may have a poststarburst stellar population.

The IRAS subsample has, on the average, bluer continuum colors and stronger line emission (particularly Hα) than the optically selected sample. Taken individually, on the other hand, their spectra are not significantly different from those of other individual mergers and share many similarities with a number of the optically selected objects. This suggests that IRAS-selected mergers may just be examples of the brightest and most active merging galaxy systems and not necessarily a distinct class of objects.

4. DISCUSSION

As can easily be seen, merger phenomena produce a very wide range of spectra. The optically selected mergers, which were chosen irrespective of the Hubble type of the galaxies in the merging pair, show spectra that could easily have come from inactive elliptical galaxies (e.g., NGC 750/751), strongly star-forming Sb and Sc spiral galaxies (e.g., NGC 3509), and starburst galaxies and AGNs (e.g., NGC 1614, NGC 3303). Clearly, the resultant star formation from a merger event varies widely depending on the conditions of each merger. Not surprisingly, there is a general correspondence between the Hubble type of the merger participants: mergers between two elliptical galaxies, for example, tend to produce elliptical-like merger spectra. On the other hand, such correspondence is partial at best, because the optical morphology of the merger participants can be very deceptive; the optical pictures of NGC 7727 and NGC 3921 are similar, for example, but are spectroscopically very different.

A detailed quantitative analysis of the spectra presented here is given in Liu & Kennicutt (1995). Among the issues discussed there are the similarities and differences between the IRAS-selected and optically selected subsamples, a statistical comparison of mergers as a class with the isolated field galaxy population, and the relationship between "E+A" galaxies and the poststarburst-type objects in this sample.

We wish to acknowledge the staff of Steward Observatory and the Multiple Mirror Telescope Observatory for their superb support. We especially thank the 2.3 m and MMT tele-
LIU & KENNICUTT

scope operators for their assistance: Dennis Means, Vic Hansen, Gary Rosenbaum, Carol Heller, Janet Robertson, and John MacAfee. We thank S. Veilleux for helpful discussions and comments. We also thank Tim Heckman for a detailed and very constructive referee's report, which helped improve the paper substantially. C. T. L. gratefully acknowledges support from NASA grant NGT-50758. This work was also supported by NSF grant AST90-19150.

REFERENCES

Liu, C. T., & Green, R. F. 1995, in preparation

...
APPENDIX B

SPECTROPHOTOMETRIC PROPERTIES OF MERGING GALAXIES

November 15, 1996

To Whom It May Concern,

This letter regards the following three published works:


As the lead author for each of these three papers, I hereby exercise my copyright and allow them to be published in my dissertation. For any further clarification, please contact the Astrophysical Journal Office in Tucson, Arizona at (520) 318-8000.

Sincerely,

Charles T. Liu
SPECTROPHOTOMETRIC PROPERTIES OF MERGING GALAXIES

CHARLES T. LU AND ROBERT C. KENNICUTT JR.

STEWART OBSERVATORY, UNIVERSITY OF ARIZONA, TUCSON, AZ 85721

Accepted 1994 November 22; accepted 1995 March 20

ABSTRACT

We present quantitative analysis of long-slit spectrophotometry of 40 merging and strongly interacting galaxy systems, in the wavelength range 3650-7100 Å. Along with optically selected objects, the sample includes 10 ultraluminous IRAS galaxies with ongoing merger activity. The mergers exhibit a very large range of spectral properties, ranging from completely evolved stellar populations to emission-line dominated starbursts and absorption-line dominated poststarburst systems. The spectral types are correlated with the morphological types of the merging galaxies, as best as they can be inferred.

The sample has much higher mean star-formation rates than isolated galaxies, as measured by Hα+[N II] line emission. The distribution of [O II] equivalent widths in the sample is very different from that of local field galaxies, but does resemble the EW([O II]) distribution for faint blue field galaxies studied in deep redshift surveys. The far-infrared (FIR) luminosities and L(FIR)/L(B) ratios of the optically selected subsample are substantially higher than that of field galaxies as a whole. The ultraluminous IRAS mergers have distinctly higher L(FIR) and L(FIR)/L(B), but are similar to the optically selected mergers at optical wavelengths; on the average, their optical continuum colors are actually somewhat bluer than the optical subsample, indicating the presence of a global, young stellar population along with heavily dust-enshrouded nuclei. The frequency of the appearance of Seyfert nuclei and LINERs in the sample is also discussed.

A considerable fraction of the mergers exhibit spectra with anomalously strong Balmer absorption, when compared to nearby normal galaxies. Many of these systems have spectra resembling those of distant E+A galaxies. A quantitative comparison of the Balmer absorption-dominated mergers with several E+A galaxies at high redshift shows that they are indeed similar and suggests that the two kinds of galaxies may be the same class of objects.

Subject headings: galaxies: interactions — galaxies: stellar content — infrared: galaxies

1. INTRODUCTION

The merger of two galaxies into a single system has long been recognized as an important process in the evolution of galaxies and their stellar populations. Observations of strongly interacting and merging galaxy systems have revealed a wide range of phenomena, indicating a great deal of evolutionary activity on both long and short timescales; these include nuclear and global starbursts (Bushouse 1986; Kennicutt et al. 1994), poststarburst galaxies (Schweizer 1990), and high molecular gas contents and concentrations (Aalto 1994), and very high far-infrared luminosities (Lonsdale, Peirson, & Matthews 1984; Joseph & Wright 1985). From the other direction have come studies of distant E+A galaxies (Aalto 1994), and very high far-infrared luminosities (Heckman 1983), high molecular gas contents and concentrations (Adams 1994), and high star-formation rates, and nuclear properties of mergers compare with those of isolated galaxies? How common are starbursts in mergers, compared to normal galaxies? How are ultraluminous IRAS mergers different from mergers without powerful far-infrared emission? What effect does the galaxy type of the merger components have on the resultant mergers' properties? The hard data to answer these questions do not yet exist in the literature.

To address the lack of data and begin to answer these questions, we have conducted a long-slit spectrophotometric survey of 40 merging galaxy systems. A detailed description of the observations, along with the spectra themselves, are presented in a companion paper (Lu & Kennicutt 1995, hereafter Paper I). In this paper we give a quantitative overview of the survey, including detailed discussions on the continuum characteristics and emission-line features.

2. THE DATA

In Paper I, we presented a comprehensive spectral atlas of the observations, along with detailed discussions of the merging galaxy sample, the spectrophotometric accuracy of the data, and the survey's qualitative characteristics. In this section, we summarize the main points of the sample selection,
observations, and aperture extraction, and we refer the reader to Paper I for a more thorough description.

2.1. Sample Selection
Most of our merging galaxy sample (28 galaxy systems) was optically selected from the Arp (1966) Atlas of Peculiar Galaxies. These mergers were selected visually and exhibit severely distorted morphologies indicated by tidal structures, peculiar galaxy shapes, and superpositions of all or part of the galaxy bodies. The sample was chosen to provide a morphological type of galaxies participating in the merger; thus, mergers of elliptical galaxies as well as spirals were included. Twenty of the objects (3C 293 and 3C 303) are radio-selected galaxies with marked morphological distortions indicative of recent merger activity (Huckman et al. 1986). The remainder of the sample consists of 10 of the most infrared-luminous galaxies in the local universe, as measured by Soifer et al. (1987) in the IRAS Bright Galaxy Survey. As shown by Sanders et al. (1988), all 10 of these galaxies are strongly interacting and merging systems, also with very distorted morphologies.

As we emphasized in Paper I, the term "merging galaxy" is primarily an observational definition rather than an interpretive one. Our targets exhibit the characteristics of galaxies that either have merged or are merging: in some cases, however, it is very difficult to be certain, based on morphological evidence alone, that the component galaxies are in fact merging. We do not exclude the possibility that the sample may contain projected pairs; we have also included one object (NGC 5257/5258) that is strongly interacting, but still has a large (~1 galaxy diameter) projected separation between the two components. For the purposes of this survey, we operationally define a "merger" as a system that appears to be in an ongoing stage of the merging process, based on the selection criteria described above. The presence of large tidal structures, distorted morphologies, physical superpositions, and similar recessional velocities of the component galaxies in all of our objects increase our confidence that we have indeed selected truly merging galaxy systems.

2.2. Observations
Most of the spectrophotometry of the merging galaxy sample was obtained using the Bo"er and Chien's spectrophotograph with a T1 800 x 800 CCD on the Steward Observatory 50 inch (2.3 m) telescope on Kitt Peak. A long-slit aperture of 2'5 x 4" was used. The mergers in the sample were measured in the wavelength range 3650-5100 Å with a 600 lines mm⁻¹ grating for a 4 Å resolution and were also measured from 4850 to 7100 Å with a 7 Å resolution, using a 400 lines mm⁻¹ grating. The remainder of the sample, primarily the fainter objects, was measured with the Red Channel Spectrograph on the Multiple Mirror Telescope on Mount Hopkins. These observations covered the wavelength range 3650-5000 Å or 4600-7500 Å with approximately 9 Å resolution, using a 1725 x 180' slits and a 300 lines mm⁻¹ grating. One object, NGC 3921, was measured with the Blue Channel Spectrograph on the MMT. All of these standard data reduction techniques were used to process the data, primarily with the CCDRED and LONGBIAS packages in the IRAF software system. Overall, the energy distributions have uncertainties of ~5% in narrow-wavelength ranges, up to a maximum of about 10%-15% peak-to-peak over broad-wavelength ranges. The averaged rms deviations across each entire spectrum are approximately half or a third as large. Apertures along the slit were traced and extracted with the APEXTRACT package; for each galaxy, all the flux along the slit was combined to create a "whole-aperture" spectrum, and smaller apertures of 1-6 kpc linear size were extracted to obtain spectra of the galaxy's nucleus or nuclei. For the trailed (integrated) spectra, where most of the spatial information is lost while the slit is trailed along the galaxy, all of the flux collected along the slit was collapsed into a single aperture.

2.3. Measurement of Spectral Features and Continuum Color
We used the SPLOT task in IRAF to measure the spectral features of the extracted spectra. For both the whole-aperture and nuclear spectra, we used direct integration to measure the line fluxes and equivalent widths for [O III] 3727 Å, H β, H α, [O ii] 4959, 5007 Å, [O i] 6300 Å, [N ii] 6548, 6583 Å, [S ii] 6717, 6731 Å, and Hα. The relatively high spectral resolution of our data allowed us to pick out the more closely clustered lines without difficulty except in only a few cases; these (primarily the Hα + [N ii] complex) were deblended with the algorithms provided in the SPLOT task. In many galaxies the Balmer lines were observed in absorption, and we measured the equivalent widths of these absorptions lines as well.

The uncertainties in our line measurements are dominated by sky subtraction errors and shot noise; we estimate the typical error to be ~±5%. Measurements of emission lines with equivalent widths less than ~2 Å are less precise, typically with ±25% error, primarily because of the systematic effects of finite resolution on measuring and detecting weak features (see Kennicutt 1992). We were also able to calibrate our emission-line measurements externally using the data of Kim et al. (1995) and Veilleux et al. (1995), who have published nuclear spectra of 18 objects in our sample. For the common objects in the two samples, our nuclear measurements of the observed emission-line flux ratios [O III]/Hα, [N ii]/Hα and [S ii]/Hα (before extinction and stellar absorption corrections) agree with theirs with ±10% variations.

The continuum colors of a galaxy are also important in determining the nature of its stellar population. We selected as our continuum color measure a "41-50" color index (Kennicutt 1992). This color was derived by measuring the relative continuum fluxes around 4100 and 5000 Å rest wavelength:

\[ 41-50 = 2.5 \log \left( \frac{f_{4100}}{f_{5000}} \right) \]

(1)

The 41-50 color for the whole-aperture and integrated spectra, along with 416 equivalent widths and [O III] and [O i] fluxes and equivalent widths for these apertures, are listed in Table 1. These apertures cover a large area of the galaxy, and whatever extinction effects caused by dust certainly could not be modeled as a uniform obscuration; so we did not attempt to correct these measurements for internal reddening due to extinction.

For the nuclear apertures, however, effective correction for the reddening effects of dust is crucial, especially if we are to...
conduct accurate nuclear emission-line diagnostics to identify AGNs. The emission-line Balmer decrement between H$_a$ and H$_b$ is the best indicator of internal dust content and its resultant reddening of the spectrum, and we use it in this work. As emphasized by Veilleux et al. (1995), however, correcting the observed Balmer decrement for the underlying stellar absorption is important for distinguishing Seyfert 2 nuclei from low-ionization, narrow emission-line (LINER) nuclei. Since the underlying Balmer absorption is masked by the line emission, it is very difficult to measure and correct for the absorption accurately.

The high resolution and signal-to-noise of our data set gave us an opportunity to use H$_a$ as an additional tool to measure extinction and stellar absorption for many of our galaxy nuclei. We first assumed an intrinsic H$_a$/H$_b$ ratio of 2.85 and an H$_a$/H$_b$ ratio of 0.469 (the decrements for case B Balmer recombination at T = 10$^4$ K). We also assumed that the equivalent width of the stellar absorption was the same in the H$_a$, H$_b$, and H$_y$ lines. We then used the net (emission - absorption) flux measured for those three lines, and computed reddening for various values of stellar absorption using both H$_a$ versus H$_b$ and H$_b$ versus H$_y$. We adopted the solutions which converged to the same values of stellar absorption, in units of equivalent width in A, and reddening, as measured by $E(B - V)$.

For galaxies where the solutions did not converge, or for galaxies with insufficient signal in H$_a$, we adopted an underlying absorption equivalent width of 4.7 A, which was the mean absorption measured in the galaxies where H$_a$ was usable. We then computed $E(B - V)$ using that value. Finally, there were a number of galaxies in which the Balmer absorption was so strong that accurate measurement of line emission was essentially impossible; for these objects, no extinction and reddening, as measured by $E(B - V)$, were presented.

Aside from the possible extinction and reddening, as measured by $E(B - V)$, we computed line flux ratios for the nuclear spectra are given in Table 2.

Once an extinction value $E(B - V)$ was derived, we used it to correct the various line fluxes with the reddening curve provided by McCall (McCall, Rybski, & Shields 1985). The observed and corrected line flux ratios for the nuclear spectra are presented in logarithmic form in Table 2.

### Table 1: Mono-aperture Merger Spectra

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<th>Object Name</th>
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<th>H$_a$ + (N II) EW (A)</th>
<th>H$_b$ EW (A)</th>
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<th>L/FIR (L$_{B0}$)</th>
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<td>221</td>
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<td>0.62</td>
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<tr>
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<td>5.7</td>
<td>-6.6</td>
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Notes: Equivalent widths presented above are positive for emission lines and negative for absorption lines. Asterisks (*) denote extended spectrum.
Source for these ratios are the line flux measurement errors. Typical uncertainties are thus ±7%–15%. These values marked by a colon (;) have uncertainties of ±40% or larger.

3. RESULTS

The spectral characteristics of our merging galaxy sample varies tremendously. A representative sampling of the wide range of observed phenomena is given in Figure 1. We observe completely inactive stellar populations, slightly and actively star-forming systems, starburst and poststarburst galaxies, and Seyfert nuclei. This general result is of course expected; since we have chosen mergers which have progenitors of all Hubble types, we should see a variety of spectra at least as wide as that of isolated galaxies of all Hubble types. In this section of the paper, we organize the results into quantifiable categories for comparison: star-formation rates, merger morphologies, infrared luminosities, AGN activity, and the poststarburst phenomenon.

3.1. Star-formation Rates: IRAS versus non-IRAS Mergers

We first consider how this merger sample compares with other galaxies in terms of current star-formation rate (SFR). The relative amount of global star formation in a galaxy system is well represented in the optical regime by the strength of the Ha + [N II] emission lines (Kennicutt 1983; [O III] 3727 Å; Gallagher, Buschhouse, & Hunter 1989; Kennicutt 1992); and continuum colors in the blue, measured in this case by the 41–50 index.

Figure 2 shows the distribution of SFRs for the merger sample, as indicated by Ha + [N II] emission and 41–50 color. We have also plotted a sample of isolated galaxies measured by Kennicutt (1992), ranging in Hubble type from E to Scd. This is not meant to be a complete comparison sample, but rather as a reference for where isolated galaxies tend to lie on this plot. Most of the mergers lie roughly in the zone occupied by the isolated galaxies. A few systems lie significantly above this zone; three of them have strong nuclear starbursts (Arp 195, [Table 1]...
Fig. 1 — Representative whole-aperture spectra from the merger sample. The spectra have been de-redshifted to $z = 0$ and normalized to unit flux units of $F_{\lambda}$ at 4300 Å rest wavelength. The wide variety of observed spectral characteristics include evolved stellar populations (NGC 750/751), slightly active (NGC 942/943), moderately active, and strongly active (NGC 5278/5279) star-forming systems, starburst (NGC 4194) and poststarburst (NGC 2623) galaxies, and galaxies dominated by active nuclei (IRAS 05189-2324).
Arp 231, and NGC 1614), three contain Seyfert nuclei (Mrk 231, Mrk 273, and 3C 305), and two contain LINERs (3C 293 and NGC 3503). Only one system, NGC 550, lies well below the isolated galaxy zone; this is an advanced merger system with a poststarburst spectrum (see § 3.5).

The mean EW([O III]) for the merger sample is 59 Å, indicating significantly enhanced SFRs compared with isolated galaxies. For comparison, a sample of 72 Sc and Sbc galaxies observed by Kennicutt & Kent (1983) had a mean EW([O III]) of 29 Å. The enhancement is particularly strong in the ultraluminous IRAS mergers (ULIGs: filled circles); their mean EW([O III]) is 88 Å, compared to 50 Å for the optically selected mergers (open circles). The line strengths in our sample may be affected by contamination from Seyfert nuclei, and also by our long-slit apertures, which underestimate the nonnuclear part of the merger systems and thus give excessive weight to the merger nuclei in the whole-aperture spectra (Kennicutt & Kent 1983). These effects alone, however, cannot account for the amount of excess Hα + [N II] observed; the global SFR is at least a factor of 2 higher among these mergers than among isolated galaxies. This result is consistent with those of Bushouse (1987) and Kennicutt et al. (1987), who also found systematically higher SFRs in strongly interacting galaxies.

In Figure 3 we compare the [O III] equivalent width distributions of this merger sample with that of a complete, magnitude-limited sample of local galaxies from Kennicutt (1992). Visually, the two distributions are clearly not the same; a K-S test shows that they are not drawn from the same parent population at the 99% confidence level. The mean EW([O III]) for the merger sample is 19 Å, compared to 11 Å for the local complete sample. Here again, the ULIG mergers (shaded boxes) have larger mean EW([O III]) than the optically selected mergers (23 vs. 17 Å).

Figure 3 is also useful for examining how merger events may relate to field galaxy evolution. Mergers are often invoked as an important mechanism driving the evolution of field galaxies at z < 1 (see, e.g., Rocca-Volmerange & Guiderdoni 1990; Broadhurst, Ellis, & Glazebrook 1992; Collés et al. 1993). One key population of objects, faint (20 < B < 22.5) blue galaxies, are believed to hold important information about both the amplitude of the evolution, as well as the physical processes involved. This population has been studied extensively in deep redshift surveys (Broadhurst et al. 1988; Colless et al. 1990, 1993), and has been shown to possess an [O III] 3727 Å line-emission distribution very different from that of local galaxy samples. It has often been suggested that these faint blue galaxies may be merging and/or interacting systems: recent observations with the Hubble Space Telescope (Grillitsch et al. 1994) support this picture.

To test this hypothesis, we have also plotted in Figure 3 (dotted line) the EW([O III]) distribution of the combined faint blue galaxy samples of Broadhurst, Ellis, & Shanks (1988) and Colless et al. (1990). Statistically, the samples are too small to determine if the distribution is the same as that of the merger sample (both y² and K-S tests are inconclusive); it should also be noted that local analogs of the faint blue galaxy EW([O III]) distribution can easily be found (e.g., Markarian galaxies; see Kennicutt 1992). Nonetheless, the qualitative similarity of the two distributions is striking, especially because the merger sample was selected independent of EW([O III]) or any continuum color criteria.

Figures 2 and 3 also show how the ULIG mergers compare with the optically selected mergers, in terms of their optical colors and SFR. Even though the IRAS objects have huge amounts of dust (Sanders et al. 1988), which serves to extinguish much of the blue luminosity of these galaxies, their 41–50 colors nonetheless fall among the bluer half of the optically selected mergers, indicating the presence of young, massive stars. Further support for this interpretation comes from the presence of strong Balmer absorption lines in many of the ULIG mergers (see Paper I). This provides direct evidence that a starburst is responsible for at least part of the high bolometric luminosities of these objects. There is probably some contamination of these results from Seyfert nuclei in several of these galaxies (see § 3.4); even so, regardless of what is going on in their nuclei in terms of QSO or AGN activity, there is apparently a great deal of global star formation going on in these ULIG mergers.

On the other hand, the IR-selected objects' colors and Hα + [N II] characteristics lie well within the bounds of the optically selected mergers. In other words, at optical wavelengths the
Type 2 mergers, which have progressed far enough in the merging process that most of the original morphological information is lost, also exhibit a wide scatter in EW(Hα + [N ii]); the scatter is smaller, though, than the two-disk mergers. Note also that if we exclude the ULIG mergers (filled circles), the optically selected type 2 objects have a much narrower range and lower median EW(Hα + [N ii]). (The exception is the starbursting galaxy NGC 4194.) One reasonable interpretation is that type 2 mergers are being observed after the epoch of peak star formation has passed. This interpretation is supported by the presence of strong Balmer absorption-dominated, poststarburst spectra in many of these objects (§3.5). This raises the possibility of using dynamical modeling of the morphology of these systems to constrain the timescales of their star-formation bursts. (Detailed investigation of this issue is beyond the scope of this paper.)

3.3. Infrared Luminosities

Even though the optically selected mergers in our sample were chosen without any knowledge of their infrared properties, a surprisingly large fraction (eight out of 28) belong to the IRAS Bright Galaxy Survey (Soifer et al. 1987). That, and the fact that the IR-selected mergers exhibit optical properties similar to the optically chosen systems, led us to examine the infrared properties of the entire sample. We searched through the IRAS Faint Source Catalog (Moshir et al. 1989) for detections of the non-ULIG sample members and found that all but five objects (the four mergers of two ellipticals each, and NGC 3303) were detected and measured by IRAS.

We then used two methods to compute the far-infrared luminosity, L(FIR), of each galaxy. One was derived by Persi et al. (1989) and used in the Kim et al. (1995) spectroscopic survey of IRAS-bright galaxies; the other was used by Rieke & Lebofsky (1986) to determine the luminosity function of IRAS galaxies in the field. Both methods produced very similar results, with the luminosity of any individual galaxy differing by no more than 25% between the two computations, and a mean difference among the entire sample of less than 10%. In this paper, we present the luminosities computed with the Rieke & Lebofsky (1986) method; for convenience, we also adopt their value of H0 = 82 km s⁻¹ Mpc⁻¹.

Figure 5a shows that the mergers are IRAS-bright not just because they contain more stars and are thus more luminous. The L(FIR)/L(B) distribution is clearly seen in Figure 5a, where we plot L(FIR)/L(B) plotted against log L(B) for the 324 galaxies in the entire IRAS-Bright Galaxy Survey (Soifer et al. 1987) and a sample of 2710 UGC galaxies detected by IRAS in both the 60 and 100 μm bands (Bothun, Lonsdale, & Rice 1989).

Figure 5b shows that the mergers are IRAS-bright not just because they contain more stars and are thus more luminous. The L(FIR)/L(B) distribution is clearly seen in Figure 5b, where we plot L(FIR)/L(B) plotted against sample fraction. Also shown in the figure is the same function for the 324 galaxies in the entire IRAS-Bright Galaxy Survey (Soifer et al. 1987) and a sample of 2710 UGC galaxies detected by IRAS in both the 60 and 100 μm bands (Bothun, Lonsdale, & Rice 1989).

Type 2 mergers, which have progressed far enough in the merging process that most of the original morphological information is lost, also exhibit a wide scatter in EW(Hα + [N ii]); the scatter is smaller, though, than the two-disk mergers. Note also that if we exclude the ULIG mergers (filled circles), the optically selected type 2 objects have a much narrower range and lower median EW(Hα + [N ii]). (The exception is the starbursting galaxy NGC 4194.) One reasonable interpretation is that type 2 mergers are being observed after the epoch of peak star formation has passed. This interpretation is supported by the presence of strong Balmer absorption-dominated, poststarburst spectra in many of these objects (§3.5). This raises the possibility of using dynamical modeling of the morphology of these systems to constrain the timescales of their star-formation bursts. (Detailed investigation of this issue is beyond the scope of this paper.)
especially the Soifer et al. sample) are biased toward FIR-bright galaxies due to their selection criteria, so our comparison still confirms the very significant \( L(\text{FIR}) \) excess exhibited by the optically selected mergers. Our results support the conclusions of Lonsdale et al. (1994), Joseph & Wright (1985), Bushouse, Lamb, & Werner (1988), and others, who have reported enhanced IR emission in strongly interacting galaxies.

Not surprisingly, the ULIG mergers, though individually very similar to members of the non-ULIG subsample in terms of their optical properties, all have distinctly higher \( L(\text{FIR}) \) per unit blue luminosity that their non-ULIG counterparts. Only four optically selected mergers have \( L(\text{FIR})/L(B) \) as high as the ULIG mergers: they are NGC 1614, Arp 238, Arp 193 (all starbursts) and NGC 2623 (a poststarburst galaxy). This suggests that the ULIG mergers may have ongoing or recently completed starbursts whose energy outputs are being channeled disproportionately into infrared wavelengths, perhaps by large amounts of surrounding dust and molecular gas. The IR luminosity could be further enhanced by recently formed, heavily dust-enshrouded AGNs in the mergers’ nuclear regions (Sanders et al. 1988).

3.4. Occurrence of Nuclear Activity

The effect of galaxy interactions, particularly strong ones, on the appearance of AGN activity is a complicated issue (see the review by Heckman 1990). Cutri & MacAlary (1985), Dahari (1985), Keel et al. (1985), MacKenty (1989), Véilleux et al. (1995), and others have found that Seyfert nuclei appear in interacting galaxies more frequently than in isolated galaxies, but Dahari (1985), Keel et al. (1985), and Bushouse (1986) have also found a deficiency of AGNs among advanced mergers and strongly interacting systems.

Figure 6 shows three emission-line diagnostic diagrams which are commonly applied to characterize the nuclear emission from galaxies: \([\text{O} \, \text{iii}] 5007 \, \AA/\text{H} \alpha \) versus \([\text{O} \, \text{ii}] 6300 \, \AA/\text{H} \alpha \), \([\text{S} \, \text{ii}] 6717 + 6730 \, \AA/\text{H} \alpha \) versus \([\text{O} \, \text{iii}] 5007 \, \AA/\text{H} \alpha \), and \([\text{O} \, \text{i}] 6300 \, \AA/\text{H} \alpha \) versus \([\text{O} \, \text{ii}] 6300 \, \AA/\text{H} \alpha \). The line ratios are computed using the Balmer absorption and extinction-corrected line fluxes described above and presented in Table 2. In all, 36 nuclear apertures had sufficient line emission to perform these diagnostics effectively. Thirteen apertures (including eight nuclei from two-elliptical mergers) had insufficient line emission, indicating no active nucleus, and were excluded from the diagnostics. Finally, seven nuclei had such strong Balmer absorption that measuring the flux of H\text{I} emission was unfeasible. For one of those nuclei (IRAS 05189–2524) a lower bound is plotted; for the remainder (Arp 220, NGC 520, NGC 2623, NGC 3509, NGC 3921, and NGC 7252), their horizontal positions are plotted on the charts assuming a Balmer absorption equal to the observed H\text{I} absorption in the spectrum, but accurate placement in the vertical \([\text{O} \, \text{iii}] 5007 \, \AA/\text{H} \alpha \) axis was not attempted.

The diagnostic charts are separated into zones, the borders of which are taken from Véilleux & Osterbrock (1987). Nuclei that lie to the left of the curve have line emission originating predominantly from H\text{II} regions, while those to the right are AGNs (Seyfert nuclei) and low-ionization, narrow emission-line regions (LINERs). The latter two classes are generally divided by the strength of the \([\text{O} \, \text{ii}] 6300 \, \AA/\text{H} \alpha \) ratio; a dashed line is drawn in the plots at \([\text{O} \, \text{ii}] 6300 \, \AA/\text{H} \alpha \) = 3, and the nuclei above that line can be considered Seyfert nuclei while those below are LINERs (Shuder & Osterbrock 1981; Keel et al. 1985).

As a check, we compared our corrected line fluxes and nuclear categorizations with those of the luminous IRAS galaxies from Sanders et al. (1988) and Veilleux et al. (1995). For the common objects in the three samples, most of the corrected line ratios measured agree to within ~10%, which is the expected variation given the accuracy of the observations. However, the \([\text{O} \, \text{ii}] 6300 \, \AA/\text{H} \alpha \) ratios are often significantly different—as much as 50% from those derived by Véilleux et al. (1995) and up to a factor of 2 from those derived by Sanders et al. (1988). The differences can be attributed to the different corrections for underlying Balmer absorption in the H\text{I} line; this is an illustration of how difficult it is to correct for the underlying absorption accurately. These systematic differences affect the vertical placement of the data points on the diagnostic charts; as discussed by Véilleux et al. (1995), this has an impact on the number of objects classified as LINERs versus Seyfert nuclei. It is also possible that in several cases, especially if nuclear starbursts are occurring, we may be observing composite spectra of AGNs and nuclear H\text{II} regions. These effects, along with the typical accuracy limits of the line measurements (~7%–15%), should be kept in mind when comparing the
the relative fractions of Seyfert nuclei, LINERs, and non-AGN nuclei.

From the charts, we see four nuclei that fit in the Seyfert category: they are the ULIGs Mrk 273, IRAS 05189+2524, and IRAS 12112+0305, and the radio-brigh object 3C 303. Also in the Seyfert category is Mrk 231, which is a broad-line Seyfert 1 by inspection of its Hα + [N ii] complex (Hamilton & Keel 1987) and is not plotted on the charts. NGC 3303B and 3C 293 are near the border between Seyfert nuclei and LINERs. There are also 10-15 nuclei that fall in the LINER category (depending on the diagnostic chart used), excluding the galaxies at the bottom of each chart; of those six objects, either three or four of them are also Seyfert nuclei or LINERs.

Of the 36 measured nuclei, at least 18 and as many as 24 (50% and 67%, respectively) have Seyfert or LINER nuclei. Considered separately, Seyfert nuclei are contained in five objects out of the sample of 40 systems (13%), and the LINER total 13 objects (33%). If we consider only the optically selected objects, we find no Seyfert nuclei and nine LINERs (22%).

There are also one radio-selected and three optically selected systems plotted at the bottom of each chart, whose horizontal positions imply that they are either Seyfert nuclei or LINERs; these “unknown” nuclei create uncertainties in the percentages of nuclei in the various categories. For comparison, the incidence rate of Seyfert nuclei in about 5% in isolated spirals (Phillips et al. 1983). It is interesting that no confirmed Seyfert nuclei at all were detected among the optically selected objects; there is on the other hand a significant excess of Seyfert nuclei in the radio- and IRAS-selected objects, which is not surprising. However, our results are not statistically significant because of our small sample size, and we thus hesitate to draw any conclusions about enhanced or deficient AGN populations in merging galaxies based on these data alone. Generally, the percentages we see appear to be consistent with those observed in samples of interacting galaxies studied by Keel et al. (1985), Dahari (1985), Bushouse (1986), Sekiguchi & Wotstencroft (1993), Veilleux et al. (1995), and others.

We have also attempted to distinguish the differences in nuclear activity with respect to merger morphological type. No nuclei in type 0 mergers were observed to have line emission stronger than 2-3 Å equivalent width; we exclude the possibility of AGNs in them. The two type 1 mergers (squares) with nuclear activity contain LINER nuclei. Only one of the Seyfert nuclei was in a type 2 (triangles) merger, with all the rest appearing in type 3 (circles) mergers. The relative absence of Seyfert nuclei in type 2 systems, which are the most advanced mergers, is consistent with the reduced Seyfert frequency in the most strongly interacting galaxies seen by Keel et al. (1985) and Bushouse (1986). This result has two caveats, however: the number of objects is relatively small, and the classification difference between type 2 and type 3 mergers is somewhat subjective and could have affected the results.

It should be mentioned that the LINERs may not have to be produced only by compact massive objects, as is the case for Seyfert nuclei. Veilleux et al. (1995) has shown observational evidence that LINERs in FIR-bright (LIRIR) galaxies are produced predominantly by shock ionization, rather than photoionization from a true AGN. Also, recent ionization models (see, e.g. Shields 1992) suggest that LINERs can be produced by massive stars in dense dust and gas environments. The violent stellar and gas kinematics in and around merger nuclei, along with starburst activity and their associated winds and supernovae, suggest that these non-AGN processes may well be responsible for many of the LINERs among the optically selected mergers (see, e.g., Harwit et al. 1987; Heckman, Armus, & Miley 1990).

3.5. Poststarburst Systems and E + A Galaxies

Perhaps the most striking result of our survey is the preponderance of Balmer absorption-line dominated spectra. These
are observed only rarely, if at all, in nearby noninteracting galaxies (Kennicutt 1992). Many of these spectra are remarkably similar to those seen in high-redshift "poststarburst" galaxies (Couch & Sharples 1987; Schweizer 1990) and "E + A" galaxies (Dressler & Gunn 1983; Oegerle, Hill, & Hoessel 1991; Wirth et al. 1993). These classes of objects, whose names are often used interchangeably, are characterized by strong Balmer absorption (geometrically 2-4 Å equivalent width in each of the Hβ, Hγ, and Hδ lines), blue (though not the bluest) continuum colors, and weak (typically less than 15 Å equivalent width) \([\text{O} \, \text{ii}]\) emission.

Under the observational definition of an E + A galaxy described above, a disproportionately large number of our merging galaxies fit into the category. If we look in the spectral region of 3600–5100 Å rest wavelength, where most E + A galaxies are identified, at least six whole-aperture or integrated spectra (Arp 193, IRAS 05189–2324, NGC 520, NGC 2623, NGC 3921, and NGC 7252) and two nuclear spectra (Arp 193 and NGC 1614–2) fit the qualitative criteria of E + A galaxies. This supports the mounting observational evidence (Lavery et al. 1992; Dressler et al. 1994, a; Couch et al. 1994) that one way E + A's are formed is through galaxy mergers.

A qualitative comparison of at least one of our mergers with previously identified E + A galaxies is illustrative. Spectrophotometry of three E + A objects obtained by Liu, Green, & Kennicutt (1992)—G515 (Oegerle et al. 1991) at \(z = 0.09\), A963–21 (Lavery & Henry 1988) at \(z = 0.20\), and CL J295–92 (Dressler & Gunn 1983, 1992) at \(z = 0.45\)—are presented in Figure 7, along with the integrated spectrum of NGC 2623. The spectral region from about 3650 to 5000 Å (rest wavelength) is shown for each object, and the spectra have been smoothed to the same rest wavelength resolution (about 6.5 Å pixel \(^{-1}\)). Aside from the differences in signal-to-noise for the four spectra, their continuum shapes and absorption-line characteristics are strikingly similar.

A more quantitative comparison is presented in Figure 8. We have plotted here the Hβ absorption equivalent width against 41–50 continuum color and the equivalent width of \([\text{O} \, \text{ii}]\) emission for the whole-aperture spectra in the merger sample (circles), a comparison sample of isolated galaxies (crosses) from Kennicutt (1992), and the three distant E + A galaxies from Figure 7 (filled triangles). In both plots, six mergers (the objects listed above with E + A-like spectra) and the three distant E + A's surpass all the other objects in \(\text{EW} (\text{H} \beta)\); their 41–50 colors range from 0.3 to 0.6, and have \(\text{EW} (\text{[O} \, \text{ii}]\) < 15 Å. Two other ULIG mergers, IRAS 08572+3915 and UGC 5101, also have very strong Balmer absorption (with Hβ equivalent width greater than 6 Å), but with stronger \([\text{O} \, \text{ii}]\) emission (\(\text{EW} = 19\) and 15 Å, respectively). On the other hand, none of the isolated comparison galaxies have \(\text{EW} (\text{H} \beta) > 6\) Å.

When comparing the spectra of the distant E + A's with our nearby mergers, it should be kept in mind that both the lower resolution and lower signal-to-noise of the distant objects' spectra can cause some significant systematic errors. Combined, they serve to blend the Hδ and Hγ lines with the Fe ii 4046 Å absorption feature and the CH "G band" at \(~ 4310\) Å, respectively, both of which can be quite strong. They also
properties of merging galaxies

Figure 8.—Diagnostic plots of Hα absorption equivalent width vs. (a) 41-50 continuum color and (b) [O III] emission equivalent width for the whole-aperture spectra. Circles: this sample. Crosses: total galaxy sample from Kasamatsu (1992). Filled triangles: high-redshift "E + A" galaxies from Fig. 7.

smear out small amounts of emission embedded in the Balmer absorption line cores and obscure any weak [O III] emission among strong higher order Balmer lines. Some of these effects are apparent, for example, when comparing the whole-aperture spectra of objects like NGC 7252 and NGC 320, obtained at fixed positions on the sky, with their integrated spectra, which are trailed across the spectrograph slit and are somewhat blended as a result (Paper I). Thus, measurements of distant E + A's will systematically underestimate [O III] line emission and overestimate Balmer absorption.

Even without compensating for this effect, the Balmer absorption-dominated mergers are still closer to the distant E + A's on Figures 8a and 8b than any of the isolated galaxies. This suggests that these merging systems may be in an intermediate evolutionary stage between E + A's and other galaxies. If we do account for this effect by slightly increasing the [O III] emission and decreasing the EW(Hα) of the distant E + A's, they and the Balmer absorption-dominated mergers would occupy approximately the same region of both Figures 8a and 8b. Combined with their nearly identical spectral shapes as shown in Figure 7, it is tempting to suggest that the two groups are in fact the same class of objects. If so, it is noteworthy that most of the E + A-like mergers have substantial Hα emission, indicating active ongoing star formation. The Hα line strength has not been measured in observations of distant E + A's in the literature, primarily because Hα is redshifted into heavily obscuring night-sky line complexes at z ≥ 0.3 and out of the optical window at z ≥ 0.5. As the nearby mergers show, their characterization as "poststarburst" galaxies may be premature, since their ongoing SFRs may still be quite high.

The link between mergers and E + A's, though tantalizingly suggested by these results, is almost certainly far from straightforward. The nature of the origins, stellar populations, and heterogeneity of E + A's as a class of objects are all complex issues, and beyond the scope of this paper; we defer these issues to Liu et al. (1993), where they will be addressed in greater depth.

4. Conclusions

This survey of merging galaxies, though only exploratory, is enlightening. Our spectrophotometric data show that mergers exhibit a wide range of spectral characteristics, from dormant, old stellar populations to starbursts, poststarbursts, and galaxies with active nuclei. We have confirmed a number of characteristics often seen in mergers, including enhanced star-formation rates and higher far-infrared luminosities. We see that ultraluminous IRAS mergers tend to have blue optical colors typical of actively star-forming galaxies and, on the average, have even stronger ongoing star formation than optically selected mergers; taken individually, however, their spectra are similar to those of many other mergers and do not form a class distinct from optically selected merging galaxy systems. We have also presented evidence that the morphological types of a merger's progenitor galaxies have a direct effect on the observed characteristics of the resultant merger; and we have shown that nearby mergers in the field can produce spectra analogous to E + A or poststarburst galaxies seen in rich galaxy clusters at high redshifts.

We wish to thank the staff of Steward Observatory and the Multiple Mirror Telescope Observatory for their superb support and assistance. We thank Sylvain Veilleux for valuable discussions, Marshall McCall for providing his reddening-extinction curve, and Tim Heckman for a detailed and very constructive referee's report which helped improve the paper substantially. C. L. gratefully acknowledges support from NASA grant NGR-07575. This research was also supported by NSF grant AST 90-19150.
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APPENDIX C

SPECTROPHOTOMETRY AND STELLAR POPULATION MODELS OF "E+A" GALAXIES

To Whom It May Concern,

This letter regards the following three published works:


As the lead author for each of these three papers, I hereby exercise my copyright and allow them to be published in my dissertation. For any further clarification, please contact the Astrophysical Journal Office in Tucson, Arizona at (520) 318-8000.

Sincerely,

Charles T. Liu
SPECTROPHOTOMETRY AND STELLAR POPULATION MODELS OF "E + A" GALAXIES

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ABSTRACT

We present long-slit spectrophotometry of eight "E + A" galaxies which have been previously identified in the literature. We use a simple two-parameter modeling scheme to test if their stellar populations can be characterized uniquely by a decaying instantaneous starburst of well-determined age superposed upon a steady state galaxy substrate. Five of the objects are well characterized by burst-plus-spiral galaxy models; two others are best fit by burst-plus-spiral galaxy models. One object cannot be described by such models, but it does resemble the spectra of some nearby merging galaxies with E + A-like spectra, possibly suggesting a multiple-burst scenario. Significant degeneracies, however, combined with the finite signal-to-noise of the data, severely limit the effectiveness of using optical spectral energy distributions alone to constrain the ages and mass fractions of the starburst components. The interpretation of E + A galaxies, especially at high redshift, must be approached cautiously.

Subject headings: galaxies: evolution — galaxies: peculiar — galaxies: starburst — galaxies: stellar content

1. INTRODUCTION

Since their identification by Dressier & Gunn (1983), the objects known as "E + A" or "poststarburst" galaxies have received a great deal of attention. Typically characterized by strong Balmer absorption lines and weak or no line emission, the spectral signature of E + A galaxies is generally believed to be caused by vigorous star formation recently preceding the epoch of observation (~10^7-10^8 yr), which has since decreased significantly or ceased altogether. It has become clear that E + A galaxies could potentially be powerful indicators of the recent past of galaxy evolution. Since the poststarburst phase lasts an order of magnitude longer than the starburst that created it, measuring the fraction of E + A's in a given population of galaxies may well be a feasible and statistically significant way to gauge the amount of increased star formation activity in the prior billion years or so.

Toward this end, a number of evolutionary models have been developed to quantify various observable parameters of E + A galaxies (see, e.g., Couch & Sharples 1987; MacLaren, Ellis, & Couch 1988; Newberry, Boroson, & Kirshner 1990; Chariot & Silk 1994; Belloni et al. 1995; Barger et al. 1995; Poggianti & Barbaro 1996). These models have allowed the use of broad- and intermediate-band filter systems to make identification of E + A's at high redshifts more feasible (see, e.g., MacLaren et al. 1988; Thimm & Belloni 1994; Belloni et al. 1995). The multipletter methods, along with spectroscopic surveys (see, e.g., Sharples et al. 1985; Lavery & Henry 1986, 1988; Fabricant, McIntosh, & Bautz 1991; Oegerle, Hoessel, & Hill 1991; Dressler & Gunn 1992; Caldwell et al. 1993), have identified significant numbers of E + A galaxies in clusters of galaxies from Coma to beyond z > 0.3. Among nearby field galaxies, studies of merging galaxies (see, e.g., Schweizer 1990; Sekiguchi & Wolstencroft 1993; Liu & Kennicutt 1995a, 1995b) have revealed surprisingly large fractions of E + A-like spectra among mergers.

While the number of known E + A galaxies is steadily increasing, the fundamental characteristic of these objects has still not been quantified: Are these galaxies in fact a distinct class? In other words, are all E + A's created by a recent starburst superposed upon a quiescent spheroidal population? Equally important to the understanding of these enigmatic galaxies is the question: If all E + A's are in fact galaxies with recently concluded starbursts, how accurately can the burst ages and strengths be determined from starburst models?

A large part of this problem lies in the broad usage of the term "E + A galaxy" in the literature. Couch & Sharples (1987) identified two well-defined categories of E + A's: blue, poststarburst galaxies (PSGs) and red, Hα strong galaxies (HDSs); nevertheless, almost every study of E + A's seems to have a slightly different definition and selection criterion. Couch & Sharples (1987), Barger et al. (1995), and others have shown that starburst models can accurately reproduce the observed properties of both PSGs and HDSs, especially their broadband colors and Balmer absorption line strengths. However, whether such models can reproduce in detail the spectral energy distributions of all E + A's across a wide wavelength range (especially in the rest frame near-UV), is uncertain.

In this Letter, we address these questions with long-slit spectrophotometry of eight E + A galaxies spectroscopically identified in the literature, including two of the three objects with which Dressler & Gunn (1983) defined the class. We then model the stellar populations of these galaxies with a simple two-parameter scheme to examine the effectiveness of using such models to determine the galaxy mass fraction consumed and the burst ages in our E + A sample.
2. SAMPLE SELECTION AND OBSERVATIONS

Our sample was chosen to reflect the population of E + A galaxies in the broadest sense, as defined by different investigators and at a wide variety of redshifts. We chose the relatively nearby (z = 0.20) objects G515, near Abell 2063 (Oegerle et al. 1991); two objects in the cluster Abell 963 (z = 0.20), identified by Lavery & Henry (1988); two "red E + A galaxies" in the cluster CL 1358+6245 at z = 0.32 (Fabricant et al. 1993; Luppino et al. 1991); two in the cluster of galaxies around 3C 295 at z = 0.46 (Dressler & Gunn 1983, 1992); and one object in the cluster CL 1601+4253 at z = 0.54 (Dressler & Gunn 1992).

All of the targets were observed with the Red Channel Spectrograph at the Multiple Mirror Telescope between 1993 June and 1994 July. We used a 300 lines mm⁻¹ grating for the wavelength region 3500–6000 Å and a 270 lines mm⁻¹ grating for the wavelength region 5500–9500 Å. Our aperture was a 5" × 180" slit; the large slit width allowed us to obtain integrated spectra of the objects and avoid problems with differential atmospheric refraction. Spectral resolution was therefore usually not limited by the slit width and ranged typically from 20 to 30 Å. Standard data reduction techniques using the IRAF software system were used to process the long-slit data, primarily with the CCDRED and LONGSLOT packages. Apertures along the slit were traced and extracted with the APEXTRACT package. The integration times for all the long-slit observations are presented in Table 1.

The spectral energy distributions (SEDs) of the eight E + A galaxies in the sample are presented in Figure 1 (Plate L10). All of the galaxies have been deredshifted using the NEWREDSHIFT task in IRAF, rebinned to a rest wavelength dispersion of 10 Å pixel⁻¹, and normalized to unity at 4500 Å. To improve the overall accuracy of the continuum shapes, four major sky features (e.g., those at 5577, 5899 Å, and the "B" and "A" bands at 6900 and 7600 Å) have been removed from the spectra. In some cases, the far-red or blue portions of the spectra have been binned into 40 Å channels to improve the accuracy of the continuum shapes.

The large range in redshift and apparent magnitude (15.2 < m* < 21.6) of the sample meant that the signal-to-noise of the spectra varied tremendously as well, from ~60 per resolution element in G515 to ~7 for the faintest objects. Similarly, the peak-to-peak uncertainties of the spectrophotometry over broad wavelength ranges vary from ~5% to ~35%; the averaged rms deviations are about half those values.

3. STELLAR SYNTHESIS MODELS

The two-parameter stellar synthesis models we used to fit the observed SEDs of the galaxies in the sample were designed to be as straightforward and general as possible. The first ("E") component was a composite spectrum of either an E/SO or Sbc galaxy template; these were created by combining the E/SO and Sbc SEDs of Coleman, Wu, & Weedman (1980) with the spectrophotometry of NGC 750 (Liu & Kennicutt 1995a) and NGC3248 (Kennicutt 1992), respectively, to create spectral energy distributions in the wavelength range 2000–10000 Å.

The second ("A") component was a starburst of finite age, as computed by the GISSEL stellar synthesis code of Bruzual & Charlot (1993). We adopted an instantaneous starburst model with a Salpeter IMF and used bursts between 10° and 2 × 10° yr old for our models. To preserve generality, we used only models produced directly by GISSEL, without interpolation; the model ages are thus spaced in approximately 10° yr intervals. Each model is labeled by its precise burst age as output by the GISSEL program. The burst models assume solar metallicity, with no chemical evolution; these limitations, however, are not likely to affect our results significantly because (1) all the E + A galaxies we are modelling are large, bright systems (M* ≈ −20), where metallicities are expected to be approximately solar; and (2) the starburst ages are all short compared to the timescales where metallicity would significantly affect the burst SED.

The family of model E + A spectra were created by simple linear combination of the E and A components described above, at differing relative flux levels. The models were fitted to the observed SEDs of the E + A galaxies with a weighted, non-negative least-squares algorithm.

Five of the eight galaxies were best fitted by an E/SO plus burst model. The best-fit burst ages were 0.2550 Gyr (A963 21), 0.7178 Gyr (CL3C 295—92), 1.015 Gyr (G515), 1.609 Gyr (CL1601—195), and 1.434 Gyr (CL3C 295—106). However, the other three galaxies could not be fitted with this combination; while good-fitting models could be found in the wavelength range 3700–7000 Å, their continuum shapes blueward of 3700 Å were all too red to be matched with the observed SEDs. The implication that some ongoing star formation was taking place in the galaxies, increasing the flux in the far blue portions of the spectra, led us to use the Schuster burst combination to fit these three objects. Two of them were fitted well by this model, with 0.2026 Gyr (A963—71) and 1.278 Gyr (CL3C 295—106) old starbursts, respectively. However, as discussed below, severe degeneracies render the age determinations for these best-fit models rather uncertain (±30% or more). The best-fit models are presented in Figure 1, superposed (dash lines) upon the observed SEDs of the sample galaxies.

The final object, CL3C 295—106, defied successful fitting with either model. Its spectrum is very blue shortward of 3500 Å rest wavelength and exhibits very strong [O III] λ5007 Å line emission (rest EW = 31 ± 3 Å) indicative of active ongoing star formation. These two spectral features make it impossible to characterize this object's stellar population with our model parameters.

4. DISCUSSION

4.1. Have All E + A Galaxies Had Starbursts?

These eight E + A galaxies form a rather inhomogeneous sample; clearly, it would be inappropriate to claim that they have all been formed by a single, recent starburst occurring in
a quiescent spheroidal population. This is not surprising, since we selected them from diverse parent samples and definitions to reflect the population of E + A galaxies in the broadest possible sense. Even so, seven out of eight share the characteristic that their SEDs are well described across a wide wavelength range by an underlying steady state galaxy stellar population of some kind (E/SO or Sbc) plus one decaying, instantaneous starburst.

The one object that could not be fitted by the simple two-parameter model, CLJ3c 295–106, may also in the post-burst class, albeit in a more complex way. This galaxy is an excellent example of how difficult it can be to classify E + A's; Dressier & Gunn (1983) detected the [O ii] line emission from this object when they classified it, but they were unable to measure the equivalent width of the emission line (31 ± 3 Å) because the redshifted [O ii] line was contaminated by the 5577 Å night sky feature in their low-resolution spectra. The strong Balmer I line absorption they measured, however, does imply the presence of a decaying starburst. There are in fact well-known analogs of this type of galaxy: many advanced merging galaxy systems exhibit both significant [O ii] emission and Balmer absorption (see, e.g., Liu & Kennicutt 1995a, 1995b, and references therein). Also, Lavery, Pierce, & McClure (1992), Lavery & Henry (1994), Couch et al. (1996), and Barger et al. (1995) have shown that the blue PSGs in distant clusters of galaxies are often mergers or interacting systems.

We illustrate in Figure 2 the qualitative similarity of CLJ3c 295–106 with two blue, E + A-like merger systems: NGC 520 (Liu & Kennicutt 1995a) and G213930+040451 (Liu et al. 1996a), at z = 0.01 and z = 0.13, respectively. Although the blue ends of the comparison galaxy SEDs are needed to confirm the starburst properties of these three objects are indeed the same, it would seem that the SED of CLJ3c 295–106 could be characterized by some combination of NGC 520 and G213930+040451. Detailed models of the stellar population of NGC 520 by Bershady (1993) have shown that it contains two starburst components: one decaying and the other ongoing and somewhat embroiled by dust. If CLJ3c 295–106 is also such an object, then all eight E + A's in our sample contain at least one recent, decaying starburst. This would lend support to the picture that, despite their many differences, all E + A galaxies have had a starburst event in their recent histories. Our results confirm and extend the conclusions of Couch & Sharples (1987), Barger et al. (1995), and others, who have successfully modeled observed E + A galaxies with starburst models similar to those we have used.
souces starbursts of 0.5088, 0.5709, 0.6405, 0.7187, 0.8064, and 0.9048 Gyr. All the models lie within 1 σ of almost every data point in the SED. The signal-to-noise required to distinguish between these models at 2600 Å rest wavelength (where the models are furthest apart in our wavelength range) at the 2σ level is about 90—an extremely difficult observational constraint for a galaxy at z = 0.46.

In Figure 30 we have plotted the same galaxy’s SED in detail from 3600 to 5100 Å, again superposing the models as described above. This is the spectral region most often used to identify E + A galaxies; but as the figure clearly shows, it is essentially impossible to tell what the true starburst age is without nearly infinite signal-to-noise. Depending on the age of the instantaneous burst, the fractional mass of the galaxy consumed in the burst ranges from 71% for the 0.9048 Gyr old burst (a fraction improbable high fraction) to 11% for the 0.5088 Gyr old burst (a factor of 2 below most E + A models in the literature).

Such severe degeneracies in age and burst mass fraction clearly cannot be ignored in any serious attempt to model E + A galaxies. Almost all the E + A synthesis models in the literature have been simple two-parameter models much like the one we have used, with a galactic substrate and a single starburst of fixed intensity; using such models to estimate burst ages and mass fractions in high-redshift E + A galaxies should be done only with great care and with the understanding that nearly identical SEDs and line strengths can be generated with widely varying initial conditions. The good-fit ranges of age and starburst mass fraction for the sample galaxies are given in Table 2.

5. CONCLUSIONS

The spectrophotometry and modeling we have presented in this work confirm that E + A galaxies are a heterogeneous class of objects with a wide range of spectral characteristics. Attempts to determine the burst ages and mass fractions of high-redshift E + A’s using simple starburst-plus-galaxy models are clearly inadequate and could lead to serious systematic errors if interpreted too boldly.

Despite the diversity of the population and degeneracy of the models, our results support the picture that all the E + A’s in our sample have undergone a massive starburst in their recent past. Also, as Table 2 shows, at least some members of the sample—especially those with the most recent starbursts (e.g., A963—71)—have burst ages and strengths that are constrained to reasonably narrow ranges. Although detailed probes of high-redshift E + A galaxies may not be possible with these techniques, studies of low-redshift E + A’s, with carefully defined samples, very high signal-to-noise resolution, and more complex modeling schemes (see, e.g., Leonard & Rose 1996; Caldwell et al. 1996) show more promise in unraveling some of these difficulties.

We are deeply grateful to Rob Kennicutt, who contributed greatly to this paper, and to Stéphane Charlot for his invaluable help with the GIESSEL stellar synthesis models. We thank Russell Lavery for providing coordinates for the E + A galaxies in Abell 963. We also thank Nelson Caldwell, Michael Gregg, David Koo, Greg Wirth, and Ann Zabludoff for valuable discussions, and the anonymous referee for constructive comments. We thank the staff of the Multiple Mirror Telescope Observatory for their superb support and assistance. C. L. gratefully acknowledges support from NASA grant NGR 50-073-04.
FIG. 1.—Spectral energy distributions of the sample galaxies (thin lines) and their best-fit galaxy plus starburst models (thick lines). CL3C 295 + 106 does not have a best-fit model. All spectra are in units of $F$, normalised to unity at 4500 Å rest wavelength. Wavelengths are in angstroms.

Lau & Green (see 45L L64)
APPENDIX D

AN OPTICAL MULTICOLOR SYSTEM FOR MEASURING GALAXY REDSHIFTS AND SPECTRAL TYPES

To be submitted for publication in The Astronomical Journal.
An Optical Multicolor System For Measuring
Galaxy Redshifts And Spectral Types

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ABSTRACT

A method of obtaining approximate redshifts and spectroscopic Hubble types of galaxies using a photometric system of six broad-bandpass filters is developed. In an evaluation of its accuracy using two distinct galaxy samples, the photometric redshifts are found to have an absolute mean deviation of ±0.05 from spectroscopically determined redshifts. Possible systematic errors of the method are investigated, including the effects of post-starburst ("E+A") galaxies and attempts to measure redshifts with incomplete color information. Applications of the technique are discussed.
D.1. Introduction

The traditional method of obtaining redshifts through spectroscopy, though accurate, is by far the most time-consuming task in any observational study of faint extragalactic objects. This is especially true for galaxies, most of which do not have spectral features so dominant as to lend themselves to quick, unambiguous redshift measurements. The need to obtain large numbers of redshifts for large samples of galaxies, however, has never been greater. Many have therefore attempted to design methods to obtain accurate redshifts of galaxies with very low spectral resolution (see, e.g., Koo 1985; Loh & Spillar 1986; Connolly et al. 1995).

We present here a photometric redshift technique we have developed, using model galaxy spectral energy distributions and a system of six optical and near-infrared broad-band filters. The technique is optimized for the analysis of galaxy data obtained from the deep multicolor survey of Hall et al. (1996a, hereafter HOGPW); and the results of this work are being applied to the data in a companion paper (Liu et al. 1996).

D.2. Model Galaxies and Colors

The six-band filter system of HOGPW consists of standard Johnson U, B and V filters, and non-standard R and I filters (called R, 175, and I86) with approximate effective wavelengths of 6620Å, 7430Å, and 8580Å respectively, and FWHM of ~1000Å each. Together, the system covers the wavelength range 3000-9000Å in approximately 1000Å intervals. The detector response included in the model colors was also that of the one used in the HOGPW survey, i.e. an engineering grade Textronix 2048 x 2048 CCD that was not thinned or coated. The transmission
functions of the filters, and the quantum efficiency curve of the CCD, are presented in Figure 1.

The model galaxy spectral energy distributions (SEDs) were assembled using the integrated spectrophotometry of Kennicutt (1992) and Coleman, Wu & Weedman (1980), for spectra representative of E/S0, Sbc, Scd and Irr (starburst) galaxies. The higher-resolution spectra from Kennicutt (1992) were spliced together with the Coleman et al. data — NGC 5248 with the Sbc galaxy, NGC 6181 with the Scd galaxy, and NGC 4449 with the Irr galaxy — to create continuous spectral energy distributions from 2000Å to 10000Å. The SEDs are presented in Figure 2. We will be using the terms “spectroscopic Hubble types” and “galaxy spectral types” often in this paper; this simply means we are referring to galaxies with the same SEDs, and hence the same implied star formation rates, as those of the representative galaxies mentioned above.

Our approach to computing the colors of our template galaxies was to place them onto a standard photometric system, to derive colors that could be used to test data on that system. Thus, we used the spectrophotometry of Hamuy et al. (1994), who have produced SEDs of a number of Southern Hemisphere standard stars across the UBVRI wavelength range. We convolved the SEDs of 14 of these stars with our filter and CCD response functions, to produce an “instrumental flux” through each filter, $I_f$:

$$I_f = \int T_f(\lambda)D(\lambda)F(\lambda)d\lambda$$

(D.1)

where $T_f(\lambda)$ is the transmission of filter $f$, $D(\lambda)$ is the quantum efficiency of the CCD, and $F(\lambda)$ is the flux of the star. In other words, we were measuring a net flux from each star as if it had been observed through a telescope with a flat
wavelength throughput of unity, with the exception of the filter and detector, and with no atmospheric extinction.

For the UBVR filters, we then used the photometric calibration of those stars by Landolt (1992) to run the PHOTCAL package in IRAF. Using this procedure, we obtained the photometric zero points and color terms with which we could transform any data simulated by our models onto the same standard UBVR system as HOGPW. The I75 and I86 filters are calibrated onto an absolute scale by HOGPW using the standard star Wolf 1346. To determine the transformation coefficients for these two filters, we processed the SED of Wolf 1346 through our procedure, and compared the instrumental flux with the absolute calibrated magnitudes defined in HOGPW to obtain the zero points. (Color terms were not used in the calibration of the I75 and I86 filters.)

The final derived parameters of the transformation from an "instrumental" magnitude to the HOGPW UBVR175I86 photometric system, calibrated onto an absolute scale with Wolf 1346, is as follows:

\[
\begin{align*}
U_{\text{inst}} &= U - 17.79 - 0.042(U-B) \\
B_{\text{inst}} &= B - 19.13 - 0.047(B-V) \\
V_{\text{inst}} &= V - 20.02 - 0.042(V-R) \\
R_{\text{inst}} &= R - 19.74 - 0.042(V-R) \\
I_{75\text{inst}} &= I75 - 19.58 \\
I_{86\text{inst}} &= I86 - 19.26
\end{align*}
\]

The formal errors for the transformation, as computed by PHOTCAL, are less than \( \pm 0.006 \) in magnitude and \( \pm 0.013 \) in the color term for each individual bandpass. Each model magnitude thus has an error of at most a few percent. The same is true for any color we choose to compute from these magnitudes.
The expected observed colors as the galaxies increase with redshift from $z=0$ to 1.1, in steps of $\Delta z=0.05$, were produced by applying K-corrections to the rest frame colors. The corrections were computed with direct numerical integration in the standard way:

$$K_f = 2.5 \log (1 + z) + 2.5 \log \frac{\int F(\lambda)T_f(\lambda)D(\lambda)d(\lambda)}{\int F[\lambda/(1 + z)]T_f(\lambda)D(\lambda)d(\lambda)}$$  \hspace{1cm} (D.2)

We present our computed model galaxy colors for the four galaxy spectral types in Tables 1-4. To check our models, we compared them with the galaxy color indices from the large photometric surveys of and Poulain & Nieto (1994), Buta & Williams (1995), and de Jong (1995). The template colors agree very well with median and mean color indices for the corresponding Hubble types, with at most ±0.05 magnitude variations.

D.3. The Photometric Redshift Method

The photometric redshift method should, in principle, output both a redshift and a galaxy spectral type for each set of input from a galaxy. As demonstrated by Koo (1985), Connolly et al. (1995) and others, a combination of sufficient wavelength coverage (i.e. near-UV to near-IR) and data from at least four filters, such as $U/B_J/R_F/I_N$, is sufficient to obtain redshifts with roughly $z \pm 0.05$ accuracy. Thus the filter set we use here, which contains six filters and roughly the same wavelength coverage, is theoretically more than sufficient for the task of finding photometric redshifts. Additionally, the division of the Johnson I-band into two narrower bandpasses (I75 and I86) gives us additional leverage at higher redshifts, as prominent spectral features (especially the 4000 Å break) are redshifted into that wavelength range.
As a first step, we need to know how well the various types of galaxies are separated in our multi-dimensional color space. In other words, how unique are the UBVRI75I86 colors of a galaxy with a given redshift and spectral type? A straightforward analysis shows that, in the (U-B)/(B-V)/(V-R)/(R-I75)/(I75-I86) color space, every galaxy redshift-spectral type pair on the previously stated binning interval is separated from every other such pair by at least 0.1 magnitude in at least one color; and the distinctions across broader wavelength ranges (e.g. B-R or R-I86) are even more pronounced.

The separation of SEDs in the multicolor space is most easily illustrated by tracing where the redshift-spectral type pairs lie on color-color diagrams. Figure 3 shows two color-color cuts in the multicolor space of the filter system, and the locations of the galaxy redshift-spectral type loci on them. These tracks can be thought of as color evolutionary tracks for non-evolving galaxies as a function of redshift. In the (U-B)/(B-R) plane, galaxies with redshifts \( z \leq 0.7 \) are well separated. Similarly, in the (B-V)/(R-I86) plane, galaxies with \( z \geq 0.4 \) are well separated. A representative shift in the colors that would be created by extinction is shown with a reddening vector for \( E(B-V) = 0.1 \).

These diagrams are also useful because they show the situations where the photometric redshift method is most and least effective. Early-type (E/S0) galaxies are very easily separated from other types, and move significantly in color space as a function of redshift; clearly, these galaxies are the ones most easily identified with this technique – a well-known fact that has been used by many authors (e.g. Im et al. 1996) and which we also use in Liu (1996). Higher-redshift blue galaxies (especially irregulars), on the other hand, are somewhat problematic; increases in redshift around \( 0.4 \leq z \leq 0.6 \), and near \( z = 1 \), only slightly change the observed
colors of these galaxy types. They are still unlikely to be confused with different
galaxy spectral types; the intrinsic errors of their redshift determinations, however,
will be larger. Some scatter can also come from variations in emission-line strength,
particularly the $\text{H} \alpha + \text{N}[\text{II}]$ complex for starburst galaxies; but the overall effect is
unlikely to be more than 0.05-0.1 magnitude in any given color, which is less than
the difference seen between almost all of the different redshift-type pairs on our
grid of models.

D.4. Comparison with Spectroscopy

The acid test of our photometric redshifts is to compare them with spectroscopic
redshifts. We used two distinct samples of galaxies, obtained independently and in
different ways, and examined how well the photometric measurements match the
spectroscopy separately and as a whole. This was done to see if our system yields
the same results with different datasets obtained with this filter set, which is what
we expect.

D.4.1. Cluster Galaxy Data

UBVRI75I86 photometry were obtained for four rich clusters of galaxies: Abell
963 ($z = 0.20$), CL1358+6245 ($z = 0.32$), CL3C295 ($z = 0.46$), and CL1601+4253
($z = 0.54$). These clusters have numerous spectroscopic redshift measurements of
cluster members of all spectral types, as well as some foreground and background
galaxies (cf. Lavery & Henry 1988; Fabricant, McClintock & Bautz 1991; Dressler
& Gunn 1992), and a large range of redshifts, making them very desirable for
testing the photometric redshift technique.

CCD imaging observations were made with the Steward Observatory 2.3-m
telescope on Kitt Peak. The central $2' \times 3'$ of each cluster were imaged in UBV with a thinned, blue-sensitive $800 \times 1200$ CCD, and the central $5' \times 5'$ were observed in $R_{I75I86}$ with a $2048 \times 2048$ CCD. Landolt (1992) broad-band standards and Massey et al. (1988) spectrophotometric standards were observed in every bandpass across all the airmass ranges observed for each night, and Wolf 1346 was always observed in $R_{I75I86}$ to calibrate the nonstandard I-filters. The data were reduced and calibrated in the usual manner with IRAF; aperture photometry was then measured for the objects in those fields with published redshifts using APPHOT. We obtained photometry with 0.1 magnitude error or better in all six passbands for 42 of these galaxies.

D.4.2. Field Galaxy Data

Spectroscopic redshifts were obtained for galaxies in the HOGPW survey, using the Kitt Peak 4-meter telescope, in parallel with observations of quasar candidates in the survey fields (Hall et al. 1996b). We refer the reader to that work for the details of data acquisition and reduction. In summary, a number of observational setups were used: a single longslit, multislits, and the HYDRA multifiber positioner and bench spectrograph. Again, the usual procedures in IRAF were used for data reduction and extraction of spectra. Redshifts were obtained by inspection of well known emission and absorption features (such as the Balmer lines, $\text{[OII]}\lambda3727\AA$, $\text{[OIII]}\lambda\lambda4959,5007\AA$, and the 4000Å break) or by cross-correlation using the XCOR task in IRAF. 38 redshifts were measured in this way; all of these objects also have $UBVRI75I86$ photometry, which are calibrated with the procedures and parameters described in HOGPW.
D.4.3. Photometric Redshifts

The algorithm we developed to determine the photometric redshift-spectral type identification for a given galaxy is a straightforward, two-step procedure. First, the U-B, B-V, V-R, R-I75, and I75-I86 colors for each galaxy were compared to the color-redshift grids for each of the four template spectroscopic Hubble types; grid locations with template colors that differed from the galaxy data by 0.3 magnitude or greater in at least two colors were designated as non-matching templates, and excluded from further consideration. This procedure typically eliminated most (~90%) of the potential template matches.

The remaining redshift-type templates were then analyzed with greater care to find the best overall match in color to the observed galaxy. Clearly, the simplest definition of a match is that the model SED matches the data more closely than any other model. This is rarely a trivial criterion to meet, however, since every real galaxy is at least slightly different from any model galaxy. In each color, there is a difference between a model SED's color and the observed color. Examination of the color distributions of the model SEDs, combined with empirical tests of choosing matches using various selection methods, led us to the following criteria for selecting matches most accurately:

<i> Each model-vs.-data comparison yields a set of \( \Delta_{i-j} \equiv (i - j)_{\text{galaxy}} - (i - j)_{\text{model}} \), where \( i-j = \text{U-B, B-V, V-R, R-I75, I75-I86} \). The most likely match is the comparison that yields the minimum \textit{largest} \( \Delta_{i-j} \). The value of such a maximum for an accurately matched redshift-type pair is typically \( \Delta_{i-j,\text{max}} \sim 0.1 \) to 0.2 magnitude.

<i>i> If \( \Delta_{i-j,\text{max}} \) is large (i.e. \( >0.2 \)) for all possible matches, the comparisons that yield the minimum \textit{second - largest} \( \Delta_{i-j} \) are also reviewed. This step
takes into account the possibility that photometry for that galaxy may have been anomalously affected in one filter, perhaps by an emission line or other spectral feature. Comparisons which yield very large values of $\Delta_{i-j}^{\text{max}} (>0.5)$, however, are not considered possible matches.

(iii) If two or more matches have similar $\Delta_{i-j}^{\text{max}}$, the best match is usually the one where the sum of $\Delta_{i-j}$'s is closest to zero. In almost all cases where this criterion is applied, adjacent colors are offset the with about the same amplitude, but with opposite signs; this is usually caused by an unusually strong spectral feature (such as an emission line) in the passband shared by the two colors. Matches with similar $\Delta_{i-j}$ characteristics are almost always of the same galaxy spectral type, with slightly different redshifts; in cases where it appears $\sum \Delta_{i-j}$ would be closest to zero in an interpolation between two adjacent redshift steps, the midpoint between those two steps is designated the most likely redshift.

(iv) Finally, if two matches meet the above criteria with the same accuracy, the one most closely matching in (U-B) or (I75-I86), for objects with likely redshift less than or greater than 0.5 respectively, is designated the more likely match. This condition is based on the fact that the separations in $F_\lambda$ of galaxy SEDs are widest in the UV and far-red wavelengths (see Figure 1).

A computer program called “GetZ” was written which automates the above analysis and outputs the four most likely best-fit matches to the data SED. The colors of the 80 sample galaxies were input into the program; inspection of the computer-generated matches yielded the final values of the galaxy spectral type and redshift identification. In all but a few cases, the program’s best-fit match was selected as the final value; in the other cases, the program’s best-fit match were at most one Hubble type and 0.05 in redshift away from the final values.
D.5. Discussion

We present in Figure 4 a direct comparison of $z_p$, the photometrically determined redshift, with the spectroscopically measured redshift $z_s$, for the galaxies in the sample. The diagonal line is not a fit to the data, but the locus of exactly perfect correspondence (i.e. $z_s = z_p$). The dispersion measure $z_p - z_s$ for the entire sample is plotted in histogram form in Figure 5.

The absolute mean deviation of all the galaxies in the sample, $\Delta_m = \Sigma(|z_p - z_s|)/N$, is 0.049. (This value corresponds to $\sigma$ in a Gaussian error distribution.) 85% of the galaxies have $|z_p - z_s| < 0.1$. As Figure 5 shows, the distribution of $z_p - z_s$ is essentially symmetric about $z_p - z_s = 0$; in fact, $\Sigma(z_p - z_s) = 0.0007$, and the error distribution is consistent with a Gaussian distribution. These results are consistent with the accuracy we expected, and with those in the literature.

D.5.1. The Effects of "E+A" Galaxies

The cluster galaxy subsample had a slightly higher $\Delta_m$ than the HOGPW subsample (0.054 vs. 0.043). The lower accuracy of the cluster sample is not statistically significant, but it is instructive to examine the cause of this slight discrepancy.

The cluster samples were all taken near the centers of rich clusters of galaxies which exhibit the so-called Butcher-Oemler effect (Butcher & Oemler 1978). Not surprisingly, a number of post-starburst, or "E+A" galaxies (Dressler & Gunn 1983; Couch & Sharples 1987; Liu & Green 1996), were observed in the CCD image fields which we used to obtain photometry of the sample galaxies. E+A galaxies have a spectrum characterized by strong Balmer absorption, weak or no
line emission, and the earmarks of an old stellar population. Their spectral energy distributions are thus a hybrid, typically with colors bluer than ellipticals but redder than late-type spirals. *A priori,* then, it seems plausible that E+A galaxies could systematically confuse the redshift-spectral type comparison scheme, since their colors are neither truly spiral nor truly elliptical.

To test this hypothesis, we have selected the E+A galaxies in the cluster sample — those objects which were designated "a" or "A" by Dressler & Gunn (1992), or "E+A" by Fabricant et al. (1991) — and plotted their $z_p - z_s$ distributions separately (with shaded bars) on Figure 5. The E+A's are clearly less accurately identified than the other galaxy types. $\Delta_m$ for the E+A's is 0.087 for 13 objects; and it is half that value (0.038 for 29 objects) for the rest of the cluster sample if the E+A's are excluded. Figure 5 shows also that the $z_p$'s which are the worst underestimates of the true redshifts (i.e. the four objects where $z_p - z_s < -0.12$) are all E+A galaxies. Although about half (6/13) of the E+A's were successfully measured to within 0.05 of their spectroscopic redshifts, our results demonstrate that E+A galaxies can increase the uncertainty of photometric redshift measurements and cause systematic underestimates of $z_p$.

D.5.2. Identifications With Incomplete Data

In any galaxy survey where a photometric redshift scheme such as ours is likely to be applied, some portion of the galaxies will have incomplete color information, such as a non-detection in one or more filters. This is especially likely for faint early-type galaxies; as Table 1 shows, if an unevolved elliptical is detected in R at a given apparent magnitude, the survey data must extend at least two magnitudes fainter in U to be detected if the galaxy is at $z=0$, and four magnitudes if it is at $z=0.4$. It is important to know if redshift identifications are still accurate or
possible with missing information, particularly U-band.

We can get some idea of what results to expect with color-color diagrams. From Figure 1, it is clear that lack of U-band data does not significantly affect the separation of high-redshift galaxies from each other; the problem with losing blue and UV data lies in confusing low-redshift, redder galaxies from higher-redshift bluer galaxies. If we exclude U-band data and use all the photometry from B redward (see Figure 6), the colors of E/S0 galaxies from $0.1 \leq z \leq 0.25$ are essentially degenerate with those of Sbc galaxies from $0.1 \leq z \leq 0.4$ and Scd galaxies from $0.2 \leq z \leq 0.6$. If both U and B data are missing, the risk of low-redshift confusion is even greater.

Empirical tests confirm the problems with measuring photometric redshifts which are suggested by the color-color plots in Figure 6. The BVRI75I86 colors for the sample galaxies were input into the "GetZ" program, and $z_p$ was determined for each object as before. This time, $\Delta_m = 0.093$, double the value of $\Delta_m$ computed with U-band data. Furthermore, galaxies which were identified as spiral or irregular with $z < 0.4$ had $\Delta_m = 0.152$; the scatter is much larger, and there is a systematic tendency to misidentify Scd and Irr galaxies near $z \sim 0.3$ as Sbc galaxies near $z \sim 0.05$.

On the other hand, $\Delta_m$ for all galaxies with $z > 0.4$ and for early-type galaxies with $z > 0.25$ were 0.048 and 0.051 respectively. Apparently there is little reduction in the typical accuracies of $z_p$ for those subsamples despite the lack of U-band data; this is also predicted by the color-color plots, and is the fortuitous result of the 4000Å break being redshifted into the V and R bands, away from the U-band. If it were possible, then, to select galaxies which are definitely early-type or at high redshift, our photometric method can still be effective for determining redshifts,
even without the U-band data which is so critical for measuring later-type galaxies at lower redshifts. We exploit this fact in Liu (1996), in which we pinpoint early-type galaxies in the redshift range $0.4 \leq z \leq 0.8$ to investigate luminosity evolution in that population.

D.6. Conclusions

We have shown that a photometric redshift method based on the broad-band colors UBVR, I75 and I86 can determine redshifts to a typical accuracy of $z = \pm 0.05$ for field and cluster galaxies, and approximate their spectroscopic Hubble types as well. This result extends the increasing amount of literature that confirms the validity of using multicolor broad-band photometry to obtain a redshift distribution for samples of galaxies. Since our system relies on colors alone, it is somewhat more versatile than systems which are dependent on other galaxy parameters such as apparent magnitude. Thus, it can be (and is being – Liu 1996; Liu et al. 1996) applied to a wider range of astrophysical problems, such as field galaxy evolution as a function of redshift.

It should be emphasized that any photometric redshift system is most effectively used as a statistical tool for measuring the redshift distribution of a galaxy sample, rather than for assigning unambiguous redshifts to individual galaxies. Just as a significant fraction of galaxies defy straightforward classification on the morphological Hubble sequence, galaxies which are not spectrophotometrically “normal” – such as E+A galaxies – can cause systematic errors in redshift and spectral type determinations. Incomplete data, such as a lack of U-band photometry, can also produce serious mistakes in $z_p$ measurements; this can be overcome, however, by selecting samples of higher-redshift and/or early-type
galaxies for study. With a healthy awareness of the method's strengths and weaknesses, and a careful attention to detail, using multicolors to obtain galaxy redshifts and spectral types is a feasible and powerful technique for use in the study of galaxy populations.
Table D.1. E/S0 Model Galaxy Colors

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This manuscript was prepared with the AAS $\text{LaTeX}$ macros v4.0.
FIGURE CAPTIONS

Fig. 1 Filter transmissions and CCD quantum efficiency vs. wavelength.

Fig. 2 Spectral energy distributions of the template galaxies, in units of $F_\lambda$ normalized to unity at 5500Å.

Fig. 3 Color evolutionary tracks for the template galaxy spectral types. The tracks assume no luminosity evolution with redshift. Each point on the tracks represents a stepwise increase in $z$ of 0.05.

Fig. 4 Estimated photometric redshift vs. spectroscopically measured redshift for galaxies from high-redshift clusters ("+") and galaxies in the HOGPW survey ("x"). The diagonal represents the locus of perfect agreement between the two different measurements.

Fig. 5 Distribution of photometric redshift errors. *Shaded bars*: E+A galaxies in the sample, identified as described in the text.

Fig. 6 Same as Fig. 3, but with color-color slices without $U$ (left) or $U$ and $B$ (right) data. Although degeneracies at low redshift are serious, high redshift galaxy types are still well separated.
Model Spectral Energy Distributions

Figure D.2
Figure D.3
Figure D.4
Figure D.5
APPENDIX E

A SEARCH FOR STAR FORMATION EVOLUTION IN EARLY-TYPE GALAXIES

To be submitted for publication.
A Search For Star Formation Evolution
In Early-Type Galaxies

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ABSTRACT

We apply a color-selection criterion to extract red galaxy candidates from the deep multi-color survey of Hall et al. (1996). We select the galaxies using red colors (V-R-I86 and R-I75-I86), then compare their bluer colors (B-R and V-R respectively) to color evolution models of non-evolving and passively evolving elliptical galaxy templates. Thus, we attempt to measure directly the excess of rest-frame ultraviolet colors in these galaxies, as an indication of their star formation evolution as a function of redshift. We see suggestions of ultraviolet excess which are inconsistent with no-evolution or passive evolution in the selected red galaxy population, and require at least some increase in the massive star formation rate since z~0.8. However, the errors in the photometry are sufficiently high at the apparent magnitudes of interest (R≤21.5) that our result is not statistically significant. We discuss the improvements to the dataset that would be required to confirm our results at a robust statistical level. Specifically, an increase of approximately 1.5 magnitudes in the B limiting depth of the sample, and 0.7 magnitudes in the V and R limiting depths, would be sufficient to achieve the desired scientific goal.
E.1. Introduction

The evolution, as a function of redshift, of ellipticals and early-type spirals – referred to hereafter collectively as "early-type galaxies" – has been carefully examined by numerous authors. The increasingly large body of observational data that has been assembled suggests a lack of active evolution in the early-type population, and points to at most "passive" color evolution, where a galaxy fades and reddens as its stellar population ages (see, e.g., Steidel, Dickinson & Persson 1994; Lilly et al. 1995; Rakos & Schombert 1995; Ellis et al. 1996; Heyl et al. 1996; Im et al. 1996). This result would suggest that early type galaxies formed at high redshift, and have not had strong episodes of star formation since that time.

One very important point, however, seems not to have been strongly emphasized in most studies of early-type galaxy evolution. Most early-type galaxies in deep samples have been selected either by their elliptical or lenticular morphology, or by red continuum colors which extend into the galaxies' rest-frame near-UV wavelengths. Such objects have, in the process of their selection, already been biased toward a lack of observable active evolution. It is definitely true that the above studies have shown that a non-evolving or weakly evolving population exists; but the question they have not truly addressed is if early-type galaxies at the present epoch as a population have evolved only passively since their formation. Have all early-type galaxies always been early-type galaxies, either morphologically or spectrophotometrically? The answer, in light of numerous theoretical and observational studies of merging galaxies (see, e.g., Barnes 1988; Liu & Kennicutt 1995; Schweizer 1996), is almost certainly no. What about most early-type galaxies? Given the strong evolution of the field galaxy luminosity function observed by Ellis et al. (1996) and others in every other galaxy type, it is
not at all unlikely that a non-negligible fraction of galaxies which were blue at the epoch of observation have since become red.

When this question is addressed in reverse – that is, can we find evidence of past evolution in present-day ellipticals and S0's? – the picture becomes even more complicated. Evidence of shells in early-type spiral galaxies (e.g., Schweizer & Seitzer 1988) and stellar population synthesis studies of nearby ellipticals (e.g., Rose et al. 1994; Fritze-van Alvensleben & Gerhard 1994; Worthey 1996) suggest that many nearby early-type galaxies may contain intermediate-age stellar populations; this would imply significant evolutionary episodes several billion years before the epoch of observation. Such activity has not been widely observed in early-type galaxies at higher \((z \sim 0.5–1)\) redshift; but that may perhaps simply be the case because such local early-type galaxies did not have early-type morphologies at that time, or because observing subtle indicators of past evolution is very difficult with current observing facilities.

In this work, we approach the question of evolution of early-type galaxies from a spectrophotometric point of view, using a deep multicolor dataset of field galaxies. By selecting high-redshift \((0.4 \lesssim z \lesssim 0.8)\) galaxies using red observed colors, we hope to choose red galaxies using roughly the same rest-frame color criteria; then by looking at the selected objects' shorter-wavelength observed colors, we can measure directly the contribution of hot, young stars to their near-ultraviolet fluxes, and infer the rate of star formation evolution between \(z \sim 0.8\) and the present.

### E.2. Galaxy Selection and Photometry

The multicolor photometric data analyzed in this work is extracted from the Deep Multicolor Survey (DMS), a CCD photometric survey of \(0.83 \text{ deg}^2\) in six
lines of sight, obtained with the Mayall 4-meter telescope at Kitt Peak National Observatory. Details of the survey are described in Hall et al. (1996, hereafter HOGPW). Briefly, the six-band filter system of HOGPW consists of standard Johnson U, B and V filters, and non-standard R and I filters (called R, I75, and I86). Together, the system covers the wavelength range 3000-9000Å in approximately 1000Å intervals. Galaxy detection and photometry were performed as described in Appendix I of Liu et al. (1996, hereafter Paper II). A total of 9,431 objects, all of which were identified as galaxies in at least three bandpasses, were detected and measured.

The number counts in the six passbands are presented in Figures 1 (a) – (f). We use these counts to estimate the completeness of our galaxy sample, in terms of numbers of galaxies detected and the magnitude limits in each color. Based on the turnover locations in the slope of the counts, dlogN/dM, we estimate the 90% completeness limits to be U~22.2, B~23.0, V~22.6, R~21.5, I75~21.5, and I86~21.2. For comparison, the 90% completeness limits for point sources in the survey from HOGPW are, respectively, 22.8, 23.8, 23.5, 23.0, 22.4 and 22.1. These numbers are consistent with the expected ≤1 magnitude increase in limiting brightness between the stars and the galaxies in a faint survey.

Since we wish to examine the galaxies that have red observed colors which correspond to early-type galaxies, we inspected Figures 2 and 3 (see below) and looked for a general red color criterion that should include all early-type galaxies with z ≥ 0.3 but few blue galaxies of any redshift. Thus we selected all galaxies redder than (V−R)>1.1 and R≤22.5 for further scrutiny. There were 659 such objects in all. Each object's image was inspected visually, to confirm that the aperture size chosen by our automatic optimization algorithm (Paper II) was
indeed appropriate, and that no undetected cosmic rays, chip defects, or intruding objects were within the aperture. In those cases, the aperture size was adjusted and the photometry recalculated accordingly.

E.3. Galaxy Color Evolutionary Tracks

To determine the color criteria that will optimally select early-type galaxies, we predict the color-color loci of red and blue galaxies in our sample using the observed spectral energy distributions (SEDs) of template local galaxies. The SEDs were assembled as described in Liu & Green (1996, hereafter Paper I), by splicing the integrated spectrophotometry of Kennicutt (1992) and Coleman, Wu & Weedman (1980), for spectra representative of E/S0, Sbc, Scd and Irr (i.e. starburst) galaxies, to create continuous spectral energy distributions from 1400Å to 10000Å. We will be using the terms "spectroscopic Hubble types" and "galaxy spectral types" often in this paper; as discussed in Paper I, this simply means we are referring to galaxies with the same SEDs, and hence the same implied star formation rates, as those of the representative galaxies mentioned above; unless otherwise noted, we will be discussing strictly spectral types and not morphological types.

We model the colors of these template SEDs as a function of redshift following the procedures discussed in Paper I. Very briefly, we convolve the SEDs with the filter transmission and CCD sensitivity functions, and factor in K-corrections computed from the SEDs. In this way, we map out the expected colors for galaxies with those SEDs as the redshift increases from $z = 0$ to 1. In Figures 2 (a) – (d), we present the tracks in the color-color planes of interest in this study: $(B-R)$ vs. $(R-I_{86})$, $(V-R)$ vs. $(R-I_{86})$, $(V-I_{75})$ vs. $(I_{75}-I_{86})$, and $(R-I_{75})$ vs. $(I_{75}-I_{86})$.

The other theoretical track we need to compute is that of a passively evolving
elliptical galaxy. We compute this track using the color evolutionary models of Bruzual & Charlot (1993, hereafter BC93). We first use the SED of an instantaneous burst with a Salpeter initial mass function which has passively evolved for $1.22 \times 10^{10}$ yr since its formation; we choose this age because the resultant SED from the BC93 models matches the rest-frame UBVRI75I86 colors of our template E/S0 galaxy to within 0.05 magnitude. In a galaxy at redshift zero, this age corresponds to a formation epoch of $z > 10$ in a universe with $H_0 = 80$ km/s/Mpc and $q_0 = 0$. Then in steps of $\Delta z = 0.05$, we adjust the age of the galaxy by the look-back time implied by this cosmology, until we reach $z = 1$. At each age on the grid, we use the BC93 models to determine the expected SED of that instantaneous burst, and compute model colors and K-corrections accordingly. Meanwhile, we also compute the colors and K-corrections for a $1.22 \times 10^{10}$ yr model redshifted from $z = 0$ to 1 in steps of 0.05 without adjusting its age, to represent a no-evolution model. The difference in color between the no-evolution model and the age-adjusted model at a given redshift is thus due to passive evolution.

In Figure 3, we plot the no-evolution tracks of our E/S0 and Sbc templates with the E/S0 track adjusted for the passive evolution computed above. As expected, the points at each redshift for the evolving tracks tend to be bluer in each color by $\sim 0.1$ magnitude than the non-evolving tracks. The exception is in B-R, where the evolving track becomes redder after $z \sim 0.6$. The passively evolving tracks are generally closer to the Sbc tracks than the non-evolving ones, but are still sufficiently well-separated that our color analysis is feasible.
E.4. How Many Early-Type Galaxies Do We Expect?

We would like a rough idea of how many early-type galaxies we are likely to find in our sample. We estimate this number using the luminosity function of Lin et al. (1996), computed from the Las Campanas Redshift Survey for galaxies with [OII]λ3727 Å line emission less than 5 Å equivalent width — a reasonable spectroscopic criterion for selecting early-type galaxies. This dataset is more appropriate for our purposes than most of the other early-type galaxy luminosity functions in the literature (e.g. Loveday et al. 1992; Marzke et al. 1994) because it is measured in the R-band, the color we are using to identify our galaxies. In the standard parameterization of Schechter (1976) for galaxy luminosity functions,

$$\phi(M) = (0.4 \ln 10) \phi^*(10^{0.4(M_*-M)})^{1+\alpha}\exp(-10^{0.4(M_*-M)})$$,

$$M_* = -20.3 + 5\log(H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1})$$, $$\alpha = -0.3$$ and $$\phi^* = 0.011 (H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1})^3 \text{ Mpc}^{-3}$$ for this early-type galaxy luminosity function. We can compute directly the number of such galaxies we expect to see in a given redshift range for a given apparent magnitude limit, by multiplying this luminosity function with the comoving volume in the redshift range included in our survey. As a check, we compute first the number of early-type galaxies we expect to see in the U-limited subsample analyzed in Paper II. From 0.02 < z < 0.15, the U-band magnitude limits from Paper II of 17.0 < U < 21.1 are shifted to 15.0 < R < 19.1, since rest frame (U−R)~2.0 for an early-type galaxy; with these limits on the Lin et al. luminosity function, we predict 52 galaxies will be observed in our survey. This is very close to the 50 early-type galaxies we actually see. From 0.15 < z < 0.30, the faint R-limit in the Paper II sample moves to 18.6 for early-type galaxies, because at z = 0.15 (U−R)~2.5; we predict 37 galaxies, exactly the number we see. Finally, from 0.30 < z ≤ 0.50, our R-limit reduces to 17.8; the Lin et al. luminosity
function predicts 1 observed galaxy, while we see 2. We are therefore confident that using this luminosity function will give us a reasonable estimate of the number of early-type galaxies we would observe in the survey, given a non-evolving population.

With an apparent R magnitude limit of 21.5, the Lin et al. luminosity function predicts 220 early-type galaxies in the redshift range $0.4 \leq z < 0.5$, 78 galaxies in $0.5 \leq z < 0.6$, and 8 galaxies in $0.6 \leq z < 0.8$. In the inclusive red galaxy sample described above, our original color selection criterion of $(V-R) \geq 1.1$ should include all of these galaxies; in fact there are 409 objects in that sample with $R \leq 21.5$. This total is consistent with having all 306 predicted galaxies in the sample, plus some additional contribution to the observed R-band counts due to evolution. (Much of the excess may also be galaxies of lower redshifts and bluer spectral types being scattered into the sample from variations in the SEDs of real galaxies, or from photometry errors.) This is another consistency check, that we are complete to $R \sim 21.5$ in our early-type galaxy selection.

Since eight objects comprise a rather small sample with which to measure the statistical effects of evolution from $z = 0.6$ to 0.8, we now check to see how many early-type galaxies we would see if we increase the magnitude limit to $R \leq 22.5$. We predict 147 galaxies in $0.6 \leq z < 0.8$ at that limit; this is an ample number of objects. However, we also predict a total of 660 objects in $0.4 \leq z < 0.8$ and $21.5 < R < 22.5$; we only see 237 such objects in the survey. Thus we are apparently only 30-40% complete in that magnitude range. At any rate, the errors in the colors at that apparent magnitude are large enough to cause serious problems in the interpretation of those data, as we discuss below.
E.5. The Color-Color Distributions of the Sample Galaxies

The method we adopt to search for evolution in the early-type galaxy sample is conceptually simple. We first find all the galaxies that can be conclusively identified as early-type galaxies using relatively red continuum colors; then, we look at their bluer continuum colors. If those blue colors do not lie on the no-evolution color tracks, we may attribute the differences to some kind of evolution. Specifically, if the blue observed colors show an excess over the no-evolution tracks, the excess is likely to be produced by massive, young stars produced by recent, active star formation.

We first try this method with the \((V-R)/(R-I86)\) diagram in Figure 4. We have selected all of the galaxies in the sample within 0.05 magnitude of the no-evolution E/S0 track in the \((V-R)/(R-I86)\) plane. All of these objects with better than signal-to-noise of 3 in their B photometry are then plotted onto the \((B-R)/(R-I86)\) plane in Figure 4a, and onto the \((V-R)/(R-I86)\) plane in Figure 4b. This pair of diagrams gives us information on early-type galaxies primarily in the range \(0.4 < z < 0.6\). The color selection we use here is rather restrictive; so if evolution away from the no-evolution locus is visible, it is more likely to be due to a systematic effect (such as evolution) rather than a random one (such as noise or cosmological scatter in galaxy colors). The result we see in Figure 4a seems very indicative of such evolution; of the \(\sim 40\%\) of galaxies with \(3\sigma\) B detections, most of them have \(B-R\) colors which lie significantly off the E/S0 tracks, and scatter blueward toward the Sbc track provided for reference. As shown by the error bars, however, the photometric errors are large; thus we defer interpretation of these results until a careful consistency check is done below.

We construct a similar pair of plots in Figures 4c and 4d. This time, we use
the (R—I75)/(I75—I86) plane to select red galaxies whose colors are within 0.20 magnitude of the no-evolution E/S0 track. This color selection gives us color information on galaxies primarily in the range 0.6≤ z ≤0.8. These points are plotted in the (V—I75)/(I75—I86) plane in Figure 4c, and in the (R—I75)/(I75—I86) plane in Figure 4d. The effect we saw in Figures 4a and 4b are qualitatively reproduced; about a third of the objects have (V—I75) which are bluer than the no-evolution E/S0 track by 1σ or more. The errors in this pair of plots, however, are even larger than in the previous pair.

The magnitude of the errors in our photometry compels us to test these results with an independent color cut of the data. The reasoning is as follows: if we choose objects that trace the non-evolving E/S0 color tracks in a blue color-color plane, they are clearly very likely to be early-type galaxies; then, if we plot those points on a redder color-color plane, they should follow the early-type galaxy tracks. If they do not, the implication is that we are not actually selecting the early-type galaxies reliably, probably because of the errors in our photometry.

Figures 5a-d show the results of this test in the two pairs of color-color planes. We have plotted in Figure 5a the objects from the (V−R)>1.1 sample which lie on and redward of the E/S0 track in the (B−R)/(R−I86) plane. These same galaxies are plotted in Figure 5b on the (V−R)/(R−I86) plane; the points do not lie along the E/S0 track as expected, but are scattered blueward toward the Sbc track. When we plot a similar population of red galaxies on the (V−I75)/(I75—I86) plane (Figure 5c), and look at their distribution on the (R—I75)/(I75—I86) plane (Figure 5d), the effect is even more pronounced; only a few of the objects are within 1σ of the no-evolution E/S0 track, and the rest are scattered blueward. This leads us to believe that our selection of early-type galaxies from this dataset is indeed
unreliable, and that our previous evidence of blue-color evolution in Figures 4a-d is not likely to be a statistically robust result.

E.6. Discussion

Ultimately, we are limited in our ability to measure evolution in the early-type galaxies of our sample by the limited depth of our survey. A straightforward calculation demonstrates this fact. At our 90% completeness limit of R~21.5, we achieve a signal-to-noise of about 10 in our photometry; for a typical early-type galaxy at z = 0.4, the observed (V−R)~1.4; thus an E/S0 at the R-limit for our sample has V~22.9. The typical signal-to-noise in V is about 8 at that magnitude; thus the (V−R) color will have a photometric error of ~0.15 magnitude. Since (V−R) for this galaxy is about 0.2 magnitude redder than (V−R) for our template Sbc galaxy at z~0.6, standard statistics predict a fairly large (~10%) probability that a "bad luck" measurement of an Sbc galaxy at z~0.6 will produce the same (V−R) color. The situation is similar for galaxies selected by (R−I75) color, because the no-evolution color tracks are separated by about the same amount (~0.2 magnitude).

We can estimate the increase in photometric accuracy we would need to make this study successful. As we noted above, there are several hundred early-type galaxies in the redshift range 0.4 ≤ z ≤0.6 brighter than R~21.5; so we are not limited by the number of potential objects to study. If we can reduce the random photometric error in V and R to ~5% each, our early-type galaxy identifications with the (V−R) color would be distinguishable from (V-R) measurements of Sbc galaxies at the 3σ level. We can achieve this by going ~0.7 magnitudes deeper in our photometry – that is, increasing our total exposure times in V and R by about
an hour in all 6 of the survey lines of sight at a 4-meter telescope (cf. HOGPW).

We would then need to augment the B-band photometry as well. The typical observed \((B-R)\approx3\) for an early-type galaxy at \(z \geq 0.4\); the difference in \((B-R)\) between an early-type galaxy and the Sbc color track is larger, however \((\sim0.5\) magnitude). Thus we need to achieve \(\sim10\%\) photometry at \(B = 24.5\), or about 1.5 magnitudes deeper than the present survey limit, to separate at the 3\(\sigma\) level measurements of early-type galaxies from Sbc galaxies. This would mean an increase of total B-band exposure time by about six hours for each survey line of sight at a 4-meter telescope. With these improvements to the dataset, we are confident that we will be able to achieve our original scientific goal of measuring star formation evolution in early-type galaxies.

Finally, we consider the ability of our color-comparison technique to measure passive evolution with this multicolor survey. As Figure 3(a) shows, the \((B-R)/(R-I86)\) color-color tracks for no-evolution and passive evolution run almost on top of each other for \(z \leq 0.6\); so we cannot distinguish a passively evolving early-type galaxy population from a non-evolving one. However, this also means that detection of active star formation evolution in our redshift range of interest can be detected with essentially the same effectiveness whether or not the early-type population is passively evolving.
REFERENCES


FIGURE CAPTIONS

Fig. 1 Raw number counts of the galaxies in the Deep Multicolor Survey, in the (a) U, (b) B, (c) V, (d) R, (e) I75, and (f) I86 passbands.

Fig. 2 Color evolutionary tracks in the color-color planes (B-R)/(R-I86) (a), (V-R)/(R-I86) (b), (V-I75)/(I75-I86) (c), and (R-I75)/(I75-I86) (d), for the template galaxy spectral types E/S0 (triangles), Sbc (squares), Scd (pentagons) and Irr/starburst (hexagons). The tracks assume no luminosity evolution with redshift. Each point on the tracks represents a stepwise increase in z of 0.05. The small numbers indicate the redshift of the nearest point on the nearest track.

Fig. 3 Color evolutionary tracks in the same planes as in Figure 2, for the non-evolving Sbc (squares), non-evolving E/S0 (open triangles), and passively evolving E/S0 (filled triangles) templates.

Fig. 4 (a) (B-R)/(R-I86) data for the galaxies in (b) which have 3σ or better detections in the B-band. (b) (V-R)/(R-I86) data for all galaxies in the red sample (see text) with (V-R) color within 0.05 magnitude or redder than the non-evolving E/S0 color track. (c) (V-I75)/(I75-I86) data for the galaxies plotted in (d). (d) (R-I75)/(I75-I86) for all galaxies in the red sample with (R-I75)>0.7. The color evolutionary tracks are drawn to the same scale as those in Figure 3.

Fig. 5 (a) (B-R)/(R-I86) data for all galaxies in the red sample with 3σ or better detections in the B-band, with (B-R) color within 0.05 magnitude or redder than the non-evolving E/S0 color track. (b) (V-R)/(R-I86) data for the galaxies in (a). (c) (V-I75)/(I75-I86) data for all galaxies in the red sample with (V-I75)>2.0. (d) (R-I75)/(I75-I86) for the galaxies in (c). The color evolutionary tracks are drawn to the same scale as those in Figure 3.
Figure E.1
Figure E.2
Figure E.2
Figure E.4
Figure E.4
Figure E.5
APPENDIX F

LUMINOSITY FUNCTIONS AND NUMBER COUNTS OF BLUE GALAXIES IN A DEEP MULTICOLOR CCD FIELD SURVEY

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Luminosity Functions and Number Counts of Blue Galaxies
In A Deep Multicolor CCD Field Survey

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ABSTRACT

A complete sample of 651 field galaxies with $17.0 < U \leq 21.1$, each with U-B-V-R-I7500-I8600 photometry, has been selected from a deep field survey which covers 0.83 deg$^2$ along six lines of sight (Hall et al. 1996, ApJS, 104, 185). Each galaxy's spectroscopic Hubble type and redshift has been measured using the photometric techniques developed by Liu (1996, Ph.D. Thesis). Of these, the 560 galaxies classified as spectral type Sbc or bluer are analyzed for signs of evolution with redshift, and for unusual star formation histories. Total number counts of the blue galaxies in the U-band give a count slope $d(\log N)/dM \approx 0.65$, consistent with previous studies. In the redshift range $0.3 \leq z \leq 0.5$, the slope steepens sharply to 0.9, indicating strong luminosity and/or number density evolution at that epoch.

The luminosity function at $0.02 < z < 0.15$ has a very steep $\alpha \approx -1.9$ down to $M(B) \approx -14$. This is consistent with the measurement of Marzke et al. (1994, AJ, 108, 437) for Magellanic spirals and irregulars, suggesting that this U-limited sample is strongly influenced by galaxies which have the spectrophotometric or surface-brightness properties of morphologically selected Sm-Im galaxies. The luminosity functions at $0.15 \leq z < 0.3$ and $0.3 \leq z \leq 0.5$ are consistent with a faint-end slope $\alpha \approx -1.5$, as found by Ellis et al. (1996, MNRAS, 280, 235), and show significant brightening of $M^*$ as found by Lilly et al. (1995, ApJ, 455, 108).

A significant population of very blue (rest frame $U$-$R < 0.3$) galaxies, with spectral energy distributions indicating strong starburst activity, is observed at $z \geq 0.3$ but not at $z < 0.3$. These may be galaxies temporarily brightened by global starbursts, which subsequently fade and redden at lower redshifts.
F.1. Introduction

The evolution of field galaxies with redshift is a phenomenon that has been intensely scrutinized, especially recently. It is a subject of debate at every level, including the most basic: what is the zero-redshift galaxy luminosity function? The common approach to this question is to model the luminosity function (LF) using the parameterization of Schechter (1976), which contains a characteristic luminosity $M^*$, a galaxy space density parameter $\phi^*$, and a faint luminosity end with power-law slope $\alpha$. Thanks to the work of numerous authors on samples of galaxies now totaling upwards of $10^4$ objects, a reasonably consistent picture is gradually forming regarding at least two facets of the local LF – with the understanding, of course, that many important details have yet to be reconciled. First, $\alpha$ is probably roughly $-0.95 \pm 0.3$ for the sample of all galaxies in the local universe (see, e.g., Loveday et al. 1992; Marzke et al. 1994a, 1994b; da Costa et al. 1994; Lin et al. 1996). Second, the luminosity functions of blue galaxies, emission-line galaxies and morphologically later-type galaxies tend to have steeper $\alpha$ than redder, non-emitting and earlier-type ones, with estimates ranging from $+0.2$ (Loveday et al. 1992) for early-type galaxies, to $-0.9$ for galaxies with $[\text{OII}]\lambda3727 \geq 5\text{Å}$ (Lin et al. 1996), to $-1.87$ for morphologically identified Sm-Im galaxies (Marzke et al. 1994b).

As we look at more field galaxy samples with fainter apparent magnitude limits, the key question becomes: how does the luminosity function, and by inference the field galaxy population, evolve with redshift? In the absence of redshift information, faint galaxy counts have been the primary tool for measuring evolution. The case for strong evolution in the field galaxy luminosity function was made, among others, by Maddox et al. (1990), who used number count data
specifically, a steep number count slope $d\log N/dM$ – to show that significant evolution may be occurring in galaxies at $17<B<21$. Multicolor surveys such as those of Koo (1986) and Jones et al. (1991) have added dimensions to number count studies by examining the color distributions of galaxies over long wavelength and magnitude baselines. The consensus appears to be that $d\log N/dM$ steepens with decreasing wavelength, suggesting stronger evolution in blue galaxies than red ones. Koo (1986) also used his multicolor data to estimate redshifts in his galaxy population – the so-called photometric redshift technique, which has since been extensively developed – and concluded that an excess of star formation is present in the field galaxy population by $z \sim 0.4$.

Ideally, redshifts for all the galaxies in a survey should be obtained when studying the evolution of those galaxies, because they provide critical information about the distances and absolute magnitudes of each object. Broadhurst, Ellis & Shanks (1988) and Colless et al. (1990; 1993) suggested that evolution of the field galaxy luminosity function, probably in the form of increased number density with redshift, was necessary to explain the redshift distribution of their magnitude-limited, $20 \leq B_J \leq 22.5$ survey. Other redshift surveys by Lilly, Cowie & Gardner (1991), Songaila et al. (1994) and Cowie et al. (1996) have concluded that little or no luminosity evolution occurs from $z = 0$ to $z \sim 1$, but suggest the appearance of an additional, starbursting population of objects at high redshift which have since faded – in essence, another sort of number density evolution.

Two recent studies have broken new ground in the study of faint galaxy luminosity functions, by obtaining redshifts for $\sim 10^3$ objects in complete samples of faint galaxies. The Canada-France Redshift Survey (Lilly et al. 1995, hereafter CFRS VI) used an I-band selection criterion to study 730 galaxies with median
redshift \( < z > = 0.56 \), and found strong, uniform brightening of the luminosity function among the blue (i.e., with colors of a template Sbc galaxy or bluer) galaxy population. The Autofib Redshift Survey (Ellis et al. 1996; Heyl et al. 1996) assembled over 1700 redshifts from a number of B-band selected samples to study an impressively large magnitude range of \( 11.5 \leq B_J \leq 24 \). They also found significant evolution of the blue galaxy luminosity function; the faint-end slope of their Schecter function parameterization was a steep \( \alpha \sim -1.5 \) in their medium and high-redshift bins (0.15 \( \leq z \leq 0.35 \) and 0.35 \( \leq z \leq 0.75 \), respectively).

Deep spectroscopic surveys such as these are extremely powerful datasets with which galaxy evolution can be studied in detail. An ideal faint galaxy survey, then, would combine faint limits, large numbers, multicolor photometry and redshifts to look at the evolution of a complete galaxy sample from many directions - luminosity functions, number counts, and spectrophotometric distributions. The primary limiting factor for obtaining such a sample is the enormous amounts of telescope time required to measure redshifts with spectroscopy; if reliable redshifts for the survey galaxies could be obtained with colors alone, such a project becomes much more observationally feasible.

In this work, we present the results from a complete U-band selected sample of galaxies from a deep, multicolor CCD survey in six optical and near-infrared passbands. We use a photometric technique to estimate the redshift and spectroscopic Hubble type of each galaxy; and with those data, we compute number counts and luminosity functions of the 560 blue galaxies in the sample. The multicolor photometry we have measured for each galaxy gives us additional leverage: we minimize possible systematic errors from K-corrections, and we can examine the relative contributions of different-colored galaxies at different redshifts.
to the observed galaxy population. Our primary goal is to examine the evolution of field galaxies; particularly, we will address the star formation histories of blue field galaxies, to which our U-band selected sample is more sensitive than samples chosen with longer-wavelength passbands. Throughout this paper we use $H_o = 100h$ km/s/Mpc ($h = 0.8$), and $q_o = 0$.

**F.2. Sample Selection; Photometric Measurement of Redshifts and Spectral Types**

Our sample has been assembled from the Deep Multicolor Survey (DMS) of Hall et al. (1996, hereafter HOGPW). The extracted dataset is a complete, magnitude-limited sample of 667 objects identified as galaxies of all types, with $17.0 \leq U \leq 21.1$ and $\sim 10\%$ photometry or better in the six DMS passbands U, B, V, R, I75 and I86. The procedures used for galaxy selection and photometry of the survey objects are detailed in Appendix I. We then apply the photometric techniques developed in Liu & Green (1996, hereafter LG96) to all the galaxies, to measure their redshifts and spectroscopic Hubble types. We refer the reader to LG96 for a thorough discussion of the method, and present only a brief summary here.

The photometric redshift/typing system we use is grounded on the basic principles first shown by Baum (1962) and later developed further by Koo (1985), Loh & Spillar (1986), Connolly et al. (1995) and others. Essentially, all galaxies not dominated by active galactic nuclei have spectral energy distributions (SEDs) in the near-UV to near-IR wavelength range distinctive enough that, even as they are redshifted into redder observed passbands, their SEDs can be distinguished from galaxies of other types and/or other redshifts with a high level
of accuracy with broad-band colors alone, given sufficient wavelength coverage. Although a photometrically determined redshift cannot compare to spectroscopy for measurements of individual galaxies, it can be an excellent statistical tool to examine galaxy populations in large surveys, for which obtaining spectroscopic redshifts is by far the most difficult and telescopically expensive task.

The photometric method of LG96 uses the UBVRI75I86 data to place galaxies into four spectroscopic categories: early-type galaxies (little or no star formation), Sbc (active star formation), Scd (strongly active star formation), and irregular (starburst). Simultaneously, the method allows us to estimate galaxy redshifts to 1σ accuracies of Δz ~ 0.05, and spectral types to within ±1 spectroscopic Hubble type, in the redshift range 0 < z < 1. This is essentially the same precision achieved by previous authors with UJFN photographic photometry (e.g., Koo 1985; Connolly et al. 1995) and multicolor photoelectric and CCD photometry (e.g., Loh & Spillar 1986). Additionally, the six-filter dataset slightly “overdetermines” the principal components of most galaxies (Connolly et al. 1995); thus, we can avoid using the apparent magnitude of a galaxy in our redshift determinations. Furthermore, the division of the standard I-band into two narrower bandpasses (I75 and I86) gives us more leverage than the broad I or photographic I_N at higher redshifts, as prominent spectral features such as Hα (at z ~ 0.3) and the 4000 Å break (at z ~ 0.9) are redshifted into that wavelength range. Finally, LG96 uses a semi-empirical algorithm, so incompleteness problems caused by “negative redshift” determinations, which occasionally happen for the Connolly et al. (1995) technique, do not occur.

As discussed in LG96, we emphasize again the difference between the spectroscopic Hubble type of a galaxy and its morphological Hubble type.
Although there is generally good correspondence between the SED of a galaxy and its position on the Hubble sequence, there are many exceptions to this rule, especially among peculiar galaxies, strongly interacting systems or mergers (see, e.g., Kennicutt 1992; Liu & Kennicutt 1995). In our analysis, we use the derived spectroscopic Hubble sequence only as a sequence of relative star formation rates and broad-band colors. Except where noted otherwise, we use in this work the terms "spectral type" and "galaxy type" to describe not the morphology of a given galaxy, but rather spectrophotometric properties.

Each galaxy in the sample was processed using the "GetZ" program as described in LG96. "GetZ" implements the photometric redshift-classification algorithm, and outputs a redshift (in discrete multiples of $\Delta z = 0.05$) and a spectral type (Early, Sbc, Scd, or Irr). Each redshift-type estimate was examined individually to make sure the algorithm had not been driven to produce an unreasonable solution by some unusual combination of colors, and adjusted where necessary to reflect a true best-fit to the data. In all, the redshift-type determinations were adjusted by more than $\Delta z = 0.025$ for 15 galaxies (out of 667, or ~2%) in the $17.0 \leq U \leq 21.1$ subsample. "GetZ" did not find an acceptable solution to 8 objects; visual inspection showed that all of these objects appeared to be point sources or nearly so. These objects were taken to be misclassified stars, and removed from the sample. There is a small possibility that these objects were AGN, whose colors are sufficiently different from the template galaxies that "GetZ" could not find redshift-type matches. Their removal in any case should not affect our conclusions, since their numerical contribution to the total sample is so small (barely 1%).
F.3. Number Counts

The basic yet informative technique of galaxy number counts is easily applied to our final, complete U-selected dataset, and we do so here. We note that 651 of the 659 galaxies lie in the redshift range 0≤z≤0.5; thus it is reasonable to adopt z = 0.5 as the upper redshift limit for our subsequent analysis. Essentially the entire sample is used, and we will be working with a well-defined, well-populated volume.

F.3.1. Total Counts

We present the plot of the number of galaxies per square degree vs. apparent U magnitude in Figure 2. Also plotted for comparison are number counts from the photographic U-band surveys of Jones et al. (1991), which cover the magnitude range 18<U<21, and Koo (1986), which cover U>19. Those two surveys agree at U≈21, but are about a factor of two apart at U≈19. (Jones et al. attributed the difference to local large-scale structure.) Our absolute member counts agree very well with Koo (1986), suggesting that the mean field density of the lines of sight covered by the DMS is similar to the SA57 and SA68 fields observed by Koo; that is, we are not likely to be strongly contaminated by clustering at z≤0.5.

We can compute the slope of the number counts with magnitude, dlogN/dM, using an error-weighted least squares fit algorithm; we derive dlogN/dM = 0.55 ± 0.05, an intermediate value between the Jones et al. (1991) and Koo (1986) measurements of 0.49 and 0.68 respectively. These consistency checks give us confidence that our sample is indeed complete and unbiased by serious selection effects or systematic errors.
F.3.2. Blue Galaxy Counts vs. Redshift

A U-band selected sample such as ours is particularly sensitive to actively star-forming galaxies; on the other hand, it samples a much smaller volume of red, early-type galaxies. A quick redshift census confirms this statement: of the 651 galaxies in the sample, 91 are classified as spectrophotometrically early-type galaxies. Of these, only two are at \( z > 0.275 \). If we are trying to examine the star formation evolution of galaxies out to \( z = 0.5 \), we could not assess the contribution of the early-type galaxies to any evolution at \( z > 0.275 \) with this sample. Perhaps more importantly, the early-type objects were identified as such precisely because they have little or no star formation; by definition, then, their inclusion in our analysis is unlikely to be meaningful. Since we wish to compare the same kinds of objects – that is, star-forming galaxies to other star-forming galaxies – at all redshifts, we elect to set aside the early-type objects for the bulk of our analyses of these data, and discuss in detail the blue galaxies – those classified as Sbc, Scd, or starburst.

To examine the change in the blue galaxy population with redshift, we divide our sample into three redshift bins: \( 0 \leq z < 0.15 \), \( 0.15 \leq z < 0.30 \), and \( 0.30 \leq z \leq 0.50 \). They contain 171, 179, and 210 blue galaxies respectively. We compute the number counts in each redshift bin, and the entire blue galaxy sample collectively, and present them in Figure 3. The magnitude bins' widths and centers have been adjusted for each plot to account for the various distributions in apparent magnitude in each redshift bin.

The progression of \( \frac{d\log N}{dM} \) with redshift is immediately evident from Figure 3. There seems to be a 2\( \sigma \) enhancement over a constant slope in the \( 19.0 < U < 19.5 \) bin, which appears in the low-redshift and total blue galaxy number count plots.
Inspection of the data shows that in two of the six survey lines of sight, there is a factor of ≤2 overdensity in that apparent magnitude range. It is likely that large scale structure is evident here, or perhaps a cluster of galaxies has appeared at z~0.1; we account for this effect when fitting dlogN/dM by assigning a lower weight to those two data points.

The best-fit value of dlogN/dM for the 560 blue galaxies is 0.64±0.06. For the three redshift bins, the best-fit values are 0.35±0.10 in the low-redshift bin (z<0.15); 0.60±0.10 in the medium-redshift bin (0.15≤z<0.30), and 0.90±0.10 in the high-redshift bin (0.30≤z≤0.50). It is well known (e.g., Green & Schmidt 1978) that dlogN/dM ~ 0.35-0.40 for a uniform distribution in a Friedmann universe with q₀ = 0, and that dlogN/dM = 0.6 for a uniform distribution in Euclidean space. Thus the implication is clear; whereas blue field galaxies appear to be uniformly distributed and at roughly constant luminosity since z<0.15, the population was definitely evolving around z~0.2; between z=0.3 and z=0.5, very strong evolution must take place in either the number density, luminosity distribution, or both. Our result is consistent with those of other authors such as Ellis et al. (1996), who also found that the bulk of evolution sets in beyond z ~0.3.

**F.4. Redshift Dependent Luminosity Functions**

Constructing the luminosity function of these blue galaxies as a function of redshift is perhaps the best way of quantifying the strong evolution indicated by the number counts. With our data, an added complication must be taken into account when computing the absolute magnitude of each galaxy: the redshift determined has a large enough error (σ = 0.05) to affect the luminosity calculation significantly. The method we use to compensate is to treat each galaxy as if it
had a probability-weighted distribution in redshift. A similar conceptualization of the problem is discussed in SubbaRao et al. (1996); using the UJFN-derived photometric redshifts of Connolly et al. (1995) and a modified version of the C-method (Lynden-Bell 1971), they are able to reproduce a spectroscopic-redshift luminosity function rather well. In this work we adopt a modified version of the $1/V_{\text{max}}$ formalism (e.g., Schmidt & Green 1986) to compute our redshift-dependent luminosity functions.

**F.4.1. The Probability-Smoothed Luminosity Distribution**

Consider a galaxy with an apparent magnitude $m_f$ in a passband $f$, and redshift $z \pm \sigma$. If $\sigma=0$, then the absolute magnitude is simply

$$M_f = m_f - 5 \log(d_L(z)) - 25.0 - k(z)$$

where $d_L(z)$ is the luminosity distance in megaparsecs, and $k(z)$ is the K-correction in that passband for the spectral energy distribution of the galaxy. The contribution of that galaxy to the relative luminosity distribution is then a delta function of amplitude unity at redshift $z$.

In the case where $\sigma > 0$, and the error distribution is Gaussian, the galaxy can be thought of as adding a series of fractional contributions to the luminosity distribution in the redshift space surrounding $z$. Such a fraction at, for example, redshift $z + \Delta z$ and with a differential redshift width $dz$, would have an absolute magnitude

$$M_f' = m_f - 5 \log(d_L(z + \Delta z)) - 25.0 - k(z + \Delta z)$$

and have an amplitude

$$N_{z+\Delta z} = P_G(z + \Delta z, z, \sigma)dz / A_G(z + \Delta z, z, \sigma)$$

where $P_G$ and $A_G$ are the Gaussian probability function and its integral, respectively.
This "fuzzing" of a galaxy's luminosity distribution in redshift space is straightforwardly achieved numerically, with a choice of $dz << \sigma$ to minimize random magnitude errors. For our dataset, $\sigma = 0.05$; our choice of $dz = 10^{-3}$. Our computational algorithm divides each galaxy into a Gaussian-weighted luminosity distribution with 300 bins, from $z-3\sigma$ to $z+3\sigma$ (i.e. $z \pm 0.15$). The entire distribution for each galaxy is normalized to unity.

With the methodology described above, in some cases the luminosity distance is supposed to be computed with redshifts that are close to zero. As noted by SubbaRao et al. (1996), this can contribute large systematic errors, because near $z = 0$ a small variation in redshift can imply an enormous change in distance modulus and in the accessible volume $V_{max}$. We therefore consider any fractional luminosity contributions with $z < 0.02$ as sampling the volume within that radius, and make $z = 0.02$ our low redshift cutoff when computing the luminosity function in the low-redshift bin. In any case, galaxies within that volume, corresponding to a recessional velocity $cz < 6000$ km/s, are subject to systematic effects from local large-scale structure and the local supercluster; accounting properly for those effects would be a task in itself, and does not lie in within the scope of this work.

Our multicolor survey gives us an additional measure of accuracy when computing the absolute magnitudes of our galaxy. As redshift increases, the accuracy of the magnitude measurement becomes increasingly affected by the inaccuracy of the K-correction – in other words, on the precision with which the SED of the galaxy is actually followed by the SED fitted to it. We can reduce our dependency on this parameter by computing the absolute magnitude of one rest-frame passband using the flux through a observed redder passband for high
redshift objects. As an example, the rest effective wavelength ($\lambda_{\text{eff}}$) of our U-filter is the same as the observed $\lambda_{\text{eff}}$ of our B-filter at $z = 0.200$, and of our V-filter at $z = 0.513$. Thus, to compute the fractional galaxy contribution to the rest-frame U-band luminosity function of an object in the range $0.15 > z > 0.40$, we use the flux through the B-filter, normalized to the rest-frame U-band flux expected for this galaxy, and the appropriate K-correction to the B-filter to compute the absolute U magnitude (cf. CFRS VI). Then for $z > 0.40$, we use the V-filter in the same way to measure the absolute U magnitude. We are thus measuring the rest-frame U-band wavelength range much more directly than if we had to rely on a large K-correction.

We compute the probability-weighted luminosity distribution for the entire sample of blue galaxies in absolute U, B, and R magnitudes. In this computation, we also include galaxies with photometric redshifts greater than 0.5, so their fractional contributions that fall within $z \leq 0.5$ are included in the luminosity functions shown below.

**F.4.2. The Modified $1/V_{\text{max}}$ Method**

In the standard $1/V_{\text{max}}$ method, each galaxy contributes a weight to the luminosity function equal to the inverse of the accessible volume within which it can be observed. The accessible volume, referred to here as $V_{\text{max}}$, is the total comoving volume within the redshift boundaries of the sample, where the given galaxy could be and fall within the selection criteria of the sample. In our case, the relevant criterion is that its apparent U magnitude lies between 17.0 and 21.1. The available volume is based on the effective solid angle of 0.830 square degree covered by the survey. A disadvantage of the $1/V_{\text{max}}$ method for deriving a spatially smoothed luminosity function is that it is sensitive to clustering within the volume; as our
number counts above showed, however, our sample is not likely to be strongly contaminated by clusters. On the other hand, a useful advantage of the \(1/V_{\text{max}}\) method is that random errors can be accurately computed using Poisson counting statistics.

In the case of a probability-weighted luminosity distribution for individual objects, it is straightforward to compute \(V_{\text{max}}\) for each fractional galaxy; correspondingly, its contribution to the luminosity function is \((1/V_{\text{max}}) \times N_{z+\Delta z}\). Assembling the luminosity function (LF) is then a matter of summing those contributions within absolute magnitude bins. The error in each magnitude bin is the square root of the total number of galaxies in the bin, \((\Sigma N_{z+\Delta z})^{0.5}\).

The obvious systematic error that comes from creating a luminosity function with "fuzzy" redshifts is that objects near the peak of the distribution will have some part of their light distributed toward brighter magnitudes. Similarly, galaxies toward the bright and faint ends of the absolute magnitude distribution will have some part of their partial contributions scattered into regions which otherwise would have few or no galaxies. This effect will cause us to underestimate slightly those parts of the LF that contribute the most light, and overestimate those parts which contribute the least. SubbaRao et al. (1996) examine this error by introducing Gaussian redshift-error spreads into Monte Carlo simulations of LFs which have an ideal Schechter (1976) function parameterization. They find that for \(\sigma(z) \approx 0.05\), \(M^*\) can be underestimated (i.e. be too bright) by as much as 0.5 magnitude and \(\alpha\) by as much as \(-0.25\) for a shallow \((\alpha = -1.0)\) Schechter LF. For a steeper, \(\alpha = -1.5\) luminosity function, the errors are reduced to \(\sim0.3\) mag in \(M^*\) and \(-0.15\) in \(\alpha\). SubbaRao et al. (1996) attempt to correct for this bias, but even the corrected values' 90% confidence contours do not include the original Schechter
function parameters. We choose not to attempt such a correction for our results.

With this caveat in mind, we use the above methodology to compute luminosity functions for our blue galaxy sample in three redshift bins in each of three colors U, B, and R: low-redshift \((0.02 \leq z < 0.15)\), mid-redshift \((0.15 \leq z < 0.30)\), and high-redshift \((0.30 \leq z \leq 0.50)\).

**F.4.3. The Low-Redshift U-Selected Luminosity Function**

In Figure 4, we present the low-redshift luminosity functions computed in U, B and R. The faint end slope is clearly very steep compared to the derived Schechter-parameterized \(\alpha\)'s of \(\sim 0.9 \pm 0.1\) found in the local blue galaxy luminosity function measurements of Lin et al. (1996), Marzke et al. (1994), Loveday et al. (1992) and others. A Schechter function fit to the data implies \(\alpha \simeq -1.9\). The Malmquist-like bias described above cannot by itself account for the large difference; such a steep slope, even if corrected for the maximum bias in \(\alpha\) suggested by SubbuRao et al. (1996), would still be far steeper than \(-1\).

Interestingly, we note that Marzke et al. (1994) computed Schechter function parameters for morphologically selected Sm-Im galaxies in the CfA Redshift Survey, and derived a value of \(\alpha = -1.87\). To test the hypothesis that their Sm-Im sample and our U-band selected sample are somehow similar, we fit our luminosity functions in all three passbands using \(\alpha = -1.87\), first finding a common \(\phi^*\) and then allowing only \(M^*\) to vary in the fit. The fit results are plotted as dashed lines in Figure 4.

The agreement is excellent in all three passbands, across the entire range of absolute magnitudes, for \(M^*(U) = -20.6 - 5\log h\), \(M^*(B) = -20.5 - 5\log h\), and \(M^*(R) = -21.5 - 5\log h\). Because of our Malmquist-like bias, and the very few
galaxies at the bright limit in the low-redshift bin, M* for these LFs should be taken in a comparative rather than absolute sense. In that case, we can state that to first order, the low-redshift blue galaxies in our sample have average rest-frame colors (U—B) \( \sim -0.1 \) and (B—R) \( \sim 1.0 \) - very nearly the rest-frame colors of our Scd template galaxy, which are -0.08 and 1.07 respectively. The fact that our U-band selection has chosen galaxies with average Scd colors is expected; this is a strong consistency check, and is convincing evidence that our probability-weighted luminosity distributions and modified 1/V_{max} method can produce luminosity functions which, although systematically biased, are reproducible and consistent enough that they can be trusted to reflect accurately any relative changes in the galaxy population.

The fact that the LF faint-end slope is so similar to that of local Magellanic spirals and irregulars suggests that we are seeing objects with spectrophotometric properties typical of Magellanic galaxies - that is, blue and actively forming stars. Aside from color selection, we may also be selecting more low-surface brightness galaxies than a typical one or two-passband sample; by using any three of six passbands to identify a galaxy, selecting an aperture size with a redder passband, and then measuring all the U-band flux in that relatively large aperture, we may be allowing more objects with low U-band surface brightness into the sample. Since low-luminosity, low-surface brightness galaxies tend to be bluer and may be quite numerous (De Jong 1995; McGaugh, Bothun & Schombert 1995), and Magellanic galaxies tend also to have lower surface brightness, the similarly steep slope of our LF and the Marzke et al. (1994) Sm-Im LF may be due in part to a less severe surface brightness selection effect in these samples compared to other samples used to compute LFs.
F.4.4. The U-selected Luminosity Function From $z = 0.15$ to 0.50

In our medium-redshift and high-redshift bins, the U-band apparent magnitude limit allows us to sample only relatively bright galaxies ($M(U) \sim -18$ or brighter). Schechter function fits to these bright-end segments of the LFs, therefore, do not constrain $\alpha$ very rigorously. We can, however, measure the relative changes in $M^*$ and $\phi^*$ by fixing the LF segments to $\alpha$'s consistent with both redshift bins, and finding the best fit to the other two parameters.

The fits to the data were all obtained using an error-weighted least squares algorithm. The first step of finding a common $\alpha$ was achieved by fitting all six LF segments (2 each in U, B, and R) with a wide range of $\alpha$'s, and determining which values allowed the best fits to all the data as a whole. It turned out that excellent fits were possible for all six segments in the range $-1.40 \leq \alpha \leq -1.70$; so we adopted the value in the center of that range, $\alpha = -1.55$. According to SubbaRao et al.'s (1996) error analysis, this value could be systematically underestimated from the true value by as much as $\Delta \alpha \sim -0.15$; and if it were not, the random error is clearly at least $\pm 0.15$. For comparison, we note that Ellis et al. (1996) found in the Autofib redshift survey $\alpha = -1.41 [-0.07, +0.12]$ from $0.15 < z < 0.35$ and $\alpha = -1.45 [-0.18, +0.16]$ from $0.35 < z < 0.75$, consistent with our chosen value given a moderate systematic $\Delta \alpha$.

Next, the best fits for the medium-redshift bin, with $M^*$ and $\phi^*$ as free parameters, were computed with fixed $\alpha$ for the U, B and R data. (Again, since these LF segments only cover the few magnitudes around $M^*$, these values are not meant to be "measurements" of these parameters. Our intent is to use them as benchmarks, to quantify our comparison of the medium and high-redshift LFs.) Finally, for each passband we started from these values and moved $M^*$ and $\phi^*$
until a good fit to the data was achieved with the high-redshift LF segment in that passband. The two faintest luminosity bins in the high-redshift R-band LF segment are affected by incompleteness; this is expected due to our U-band selection, and we do not include them in the fits. Since the high-redshift segments barely reach M*, φ* can easily be varied as much as a factor of 50% or more (with a smaller corresponding move of M*) and excellent fits can still be achieved; we thus chose the smallest possible change in φ* that produced a good fit to the data. In this way, we can give a lower bound to the number density evolution we might expect as the average redshift of our sample increases from <z>~0.2 to <z>~0.4.

The six LF segments in the two higher redshift bins, along with their fitted Schechter functions in the relevant luminosity ranges, are presented in Figure 5. (The values for the Schechter fits shown in Figures 4 and 5 are for h = 1.) The data in all three colors shows a consistent evolutionary picture from our medium-redshift to high-redshift bins: M* brightens by 0.3 magnitude, and φ* increases 15-30% in each bin. The formal errors to these fits are relatively large — ~10% in M*, ~20% in φ* — but the trend is clear, even upon visual inspection of Figure 5. Our fitting procedure, which attempts to produce the smallest possible shift in φ*, also supports the idea that we are seeing real evolution in the galaxy population.

Comparison with the CFRS and Autofib data shows that our results are consistent with the evolution observed in those surveys. In CFRS VI, M* in their blue galaxy luminosity functions brightens by about 1 magnitude, assuming no change in φ*, between their redshift bins 0.2 < z < 0.5 and 0.5 < z < 0.75. Our brightening of 0.3 magnitude occurs largely within their low-redshift bin; it can be increased to ~0.5 magnitude if we fit the parts of our LF that correspond to the same magnitude ranges observed in the CFRS and hold φ* fixed. Both these
values are consistent with an incremental brightening of $M^*$ from $<z>\sim0.2$ to $<z>\sim0.4$, which leads to a total brightening of $\sim1$ magnitude by $<z>\sim0.6-0.7$. Heyl et al. (1996) parameterized the Autofib data with redshift-dependent evolving luminosity functions as a function of galaxy spectral type (determined by cross-correlation of spectral features with galaxy templates); based on those models, we can estimate the expected evolution in the combined population of Sbc, Scd and Sdm/starburst spectral types from $<z>\sim0.2$ to $<z>\sim0.4$. For that interval, $M^*$ would brighten by $\sim0.1$ magnitude and $\phi^*$ would increase $\sim50\%$. This solution is also allowed by our fits, which as we mentioned above can easily accommodate an increase in $\phi^*$ by reducing $\Delta M^*$.

### F.5. A Transient Starbursting Population At $z>0.3$

All of our measurements of the evolution of the blue galaxy LF with redshift are consistent with those observed by other workers using deeper surveys. We can now use the added dimension of multicolor observations in our survey to examine the spectrophotometric properties of the galaxies themselves, and see which kinds of galaxies are contributing most to the evolution.

We can glance at the distribution of color vs. magnitude for the entire blue galaxy sample in Figure 6. The rest frame $(U-R)$ color is effective as a rough indicator of star formation, and has a large enough range (in our templates: 1.2 for Sbc, 1.0 for Scd, 0.2 for starbursts) to spread the galaxies in color space to avoid confusion between galaxy spectral types. We plot rest frame $(U-R)$ vs. absolute $R$ magnitude, with different symbols representing the different redshift bins. The majority of the sample objects lie around $(U-R) \sim 0.9$, as expected for a population dominated by late-type spirals and starburst galaxies. The reddest galaxies in the
sample have \((U-R) \sim 1.5\); this is determined by our blue galaxy selection criterion. As \((U-R)\) decreases, a progressively stronger young stellar population dominates the luminosity, implying increasingly active star formation. A dotted line at \((U-R) = 0.3\) is provided in the figure, to mark the approximate color of a global starburst or HII galaxy such as NGC 4449, the basis of our starburst galaxy template.

Near and below this line at \((U-R) = 0.3\), objects from the high-redshift bin appear to outnumber objects from the lower-redshift bins by factors of several. At first glance this may not seem surprising, since the high-redshift bin samples a comoving volume about twice that of the two lower redshift bins combined. The respective fractions of these objects in their bins, however, is significantly different: \(\sim 5\%\) for the low-redshift bins, compared to \(\sim 15\%\) at high redshift. The difference cannot be attributed to random errors alone.

A quantitative display of this effect is shown in Figure 7. The galaxies have been placed into 15 bins – five R-band luminosity bins, in each of the three redshift bins – and plotted in histogram form. (Bins with no galaxies are not plotted.) In the vertical direction, going down, the galaxies in the same redshift bin increase in luminosity. Down each column, in each redshift, we see the well known color-magnitude relation, where brighter galaxies tend to have redder colors. But in the second and third rows the magnitude bins remain constant, and only redshift changes; although the number of galaxies in each bin varies widely, the color evolution with redshift is evident and dramatic. The median \((U-R)\) color of the high-redshift bins from \(-16.5 < M(B) < -21.5\) are about 0.5 magnitude bluer than those at medium-redshift, and \(\sim 0.8\) magnitude bluer than those at low-redshift.

We test the possibility that this is a magnitude-limited selection effect by plotting the same figure with a brighter limiting magnitude of \(U \leq 20.8\) instead of
U<21.1, and present it in Figure 8. The number of galaxies is reduced, so the statistics are less reliable. Nonetheless, the same effect is observed, and the median colors for each bin are essentially unchanged. We also check that the effect is not somehow caused by the (U-R) color by plotting the same histograms for (U-B), in absolute B magnitude bins (Figure 9). The colors are compressed somewhat, as the range of (U-B) from Sbc to starburst is about half that of (U-R); but again the effect is obvious, especially in the third row, where the median (U-B) color moves from $-0.25$ at high-redshift to $-0.05$ at medium-redshift to $+0.05$ at low-redshift. Finally, we examine the U, B, and R images of these galaxies in the photometric survey; each galaxy appears to have an atypically bright U-band image, with no signs of undiscovered cosmic rays, uncorrected bad pixels, or other problems in the data that would have artificially caused the colors to be so blue. The implication seems to be that a significant population of very blue, probably starbursting galaxies appears at $z \gtrsim 0.3$ which are not observed at $z < 0.3$.

**F.6. Discussion**

The idea of a bursting population at relatively high redshift that has since faded has been put forth, among others, by Broadhurst, Ellis & Shanks (1988), Lacey & Silk (1991), Babul & Rees (1992), and Cowie et al. (1996). The application of those models, however, is primarily to the so-called “faint blue galaxy problem,” where galaxy counts beyond B~22 are much greater than expected for a non-evolving population. Our blue galaxy survey from the DMS only reaches B~21; thus it is probably inappropriate to call the excess starburst galaxies in our high-redshift bin “faint blue galaxies” in the above sense. We will not try to address that problem here, though it is certainly possible that our starbursts may be related to that faint
blue galaxy population.

What these high redshift starburst galaxies can help explain may be the general evolution of the blue galaxy luminosity function. We have confirmed the results of Maddox et al. (1990), CFRS VI, Ellis et al. (1996), Heyl et al. (1996) and others that evolution does occur in the blue field galaxy population, and that the evolution is observationally discernible by \( z \approx 0.3 \). The number density and/or luminosity increases we are seeing may in fact be caused in part by the appearance of these starbursting objects. No galaxy can long sustain the gas consumption rate required to produce the strong global star formation implied by their \((U-R)\) and \((U-B)\) colors; so these objects should eventually fade, then redden, and eventually blend into the more numerous population of galaxies with lower, steady-state star formation.

Can such starburst galaxies fade into the background of more quiescent galaxies in the time between our high-redshift and medium-redshift bins? We examine this question using the population synthesis models of Bruzual & Charlot (1993), which give us quantitative estimates of the colors and magnitudes of aging starbursts. We first consider the most extreme case, of a galaxy starbursting so strongly that its underlying stellar population contributes negligibly to the total luminosity of the galaxy. For this case, we use an instantaneous burst model with a Salpeter initial mass function. In our chosen cosmology, \( 1.4 \times 10^9 \) years elapse between \( z=0.4 \) and \( z=0.2 \), roughly the mean redshift of the galaxies in our high-redshift and low-redshift bins respectively. We assume that we are observing the burst at an age where the rest frame \((U-B)\) and \((U-R)\) colors most closely match those of the starburst galaxies in the high-redshift bin. That age would be \( 6 \times 10^7 \) years, when \((U-B) = -0.49\) and \((U-R) = 0.28\). After \( 1.4 \times 10^9 \) yr the
R magnitude of the burst will have faded some 4.4 magnitudes according to the Bruzual & Charlot (1993) models, and the colors will have reddened to (U-B) = 0.24 and (U-R) = 1.3. If M(R) ~ -21 at 6 \times 10^7 \text{ yr}, the post-burst evolution moves the galaxy well into the middle of the locus where most of the low-redshift galaxies lie in Figure 6. Our survey would not be able to detect such an object at \( z \sim 0.2 \).

A somewhat less extreme case would be a galaxy which has a global starburst triggered in it. In one possible scenario, explored by Charlot & Silk (1994), Belloni et al. (1995), Barger et al. (1996) and others, the starburst continues at a constant star formation rate for a short time (typically $10^8$ to $10^9$ yr), then stops after converting into stars a gas fraction equal to some percentage (typically 10-20\%) of the final mass of the galaxy. After this burst is over, all star formation is truncated. We choose for our comparison a late-type spiral galaxy which undergoes a Salpeter-IMF starburst lasting $10^8$ yr that consumes 10\% of the final galaxy mass. If we select a time after the starburst begins when the galaxy has UBR colors similar to our template starburst, these authors show that (U-R) will again be \( \sim 1.3 \) after 1.4 Gyr; the R-band fading would be a more modest 1.3 magnitudes. This burst scenario would move our M(R) ~ -21 bursting galaxy into the middle of the medium-redshift galaxy locus, again becoming largely anonymous within a large reservoir of ordinarily-colored blue galaxies.

If fading and reddening of the burst is indeed the mechanism for removing starburst galaxies from view nearward of \( z \sim 0.3 \), one strong test of this population's effect on the blue galaxy luminosity function would be to see if removing the excess starburst galaxies leads to a luminosity function consistent with a passively evolving galaxy population since \( < z > \sim 0.4 \). Our data do not go faint enough to let us conduct this test rigorously; however, if we remove those galaxies from
the high-redshift bin altogether – that is, assign a color cutoff of \((U-R)>0.5\) – and re-compute the luminosity function with the remaining galaxies, we get what is presented in Figure 10. We are able to fit the LF with \(\alpha = -0.9\), measured for local blue galaxies by Lin et al. (1996), and \(\phi^* = 0.0075\), about the number for the sum of local late-type spirals as measured by Marzke et al. (1994). By no means should this successful fit be taken as evidence that the LF would only evolve passively if the \(z \geq 0.3\) excess starburst population is removed; the lack of lower-luminosity data points means that the fit is not at all strongly constrained, especially the value of \(\alpha\). What we illustrate in Figure 10 is that our data are consistent with the hypothesis that the fading-burst picture can account for much of the evolution in the blue galaxy luminosity function. A firm conclusion can only be drawn when additional data for galaxies at fainter absolute magnitudes become available.

### F.7. Conclusions

We have shown that an optical multicolor survey of field galaxies, such as the Deep Multicolor Survey, can be a very powerful tool for studying galaxy evolution. Such a survey offers concrete advantages over surveys with only one or two passbands: the two most relevant in this work are our decreased dependence on K-corrections for accurate absolute magnitude determinations, and the additional leverage we obtain from examining the spectral energy distributions of each galaxy. In addition, while there is ultimately no substitute for secure spectroscopic redshifts, we can extract almost as much information about luminosity functions and evolution as a function of redshift as true redshift surveys by using a photometric redshift-classification technique such as we have, with orders of magnitude less telescope time. We have developed a modified version of the \(1/V_{\text{max}}\) method for computing luminosity
functions using galaxies with photometrically determined redshifts. The method's
systematic errors make absolute determinations of $M^*$ and $\alpha$ difficult; but relative
changes in the luminosity functions are reliable, and can be used to measure
differential evolution effectively.

We have assembled a complete, magnitude limited sample of 560 galaxies
with rest-frame multicolors as blue as, or bluer than, a typical Sbc galaxy. The
low-redshift ($0.02 \leq z < 0.15$) luminosity function for this sample has a very steep
faint-end slope, which turns out to be exactly consistent with the measurement of
$\alpha$ for Magellanic spirals and irregulars from the CfA Redshift Survey (Marzke et
al. 1994). The implication is that our blue galaxies and those Sm-Im galaxies are
drawn from essentially the same steep-sloped population. Whether that population
is defined by its spectrophotometric, morphological or surface-brightness properties
is uncertain, and merits further investigation.

$U$-band number counts vs. redshift, and comparison of the luminosity function
segments in medium-redshift ($0.15 \leq z < 0.30$) and high-redshift ($0.30 \leq z < 0.50$)
bins, demonstrate significant evolution in the galaxy population which is clearly
visible by $z \gtrsim 0.3$. The nature, amplitude and epoch of the evolution we observe
are consistent with those found by the Canada-France Redshift Survey and the
Autofib redshift survey. Using the broad wavelength coverage for each galaxy in
our survey, we use color-magnitude diagrams and histograms in $(U-B)$ and $(U-R)$
vs. absolute magnitude to identify an excess population of apparently starbursting
galaxies in the high-redshift bin which does not appear at lower redshift. It is
plausible that these objects have been temporarily brightened by their global
starbursts, and will redden and fade into obscurity by $z \sim 0.2$. These galaxies may
be contributing significantly to the observed evolution of the blue galaxy luminosity
function at $z \gtrsim 0.3$. If this is true, what makes the particular epoch $z \simeq 0.3$ the threshold past which these starbursts are no longer produced? The answer to that question will contribute greatly to our understanding of field galaxy evolution.

F.8. Appendix I

The Deep Multicolor Survey: Galaxy Detection and Photometry

A detailed description of the Deep Multicolor Survey (DMS) is given in HOGPW. Here, we summarize its characteristics, and describe how the galaxy sample is derived.

The DMS was obtained with the Mayall 4-meter telescope at KPNO, in direct imaging mode at prime focus, with an engineering quality 2048×2048 Tektronix CCD. The survey covers 0.83 deg$^2$ along six lines of sight at high galactic latitude. Each field was observed with six filters: standard Johnson UBV; a custom R filter calibrated to the Kron-Cousins system; and two custom I filters with $\lambda_{\text{eff}} = 7430$ Å and 8520 Å respectively, referred to hereafter as I75 and I86. Reduction and calibration of the images, and the establishment of the photometric system for the nonstandard filters, was performed as described in HOGPW.

The assembly of the object catalog was performed in several steps. First, the Faint Object Classification and Analysis System (FOCAS; Valdes 1982a) was used to identify objects using its default ("built-in") detection filter. The detected objects were classified using the "resolution" task in FOCAS (Valdes 1982b) as star, fuzzy star, galaxy, diffuse object, or noise, using templates generated from a point source function empirically determined from the CCD image. An inclusive,
automatically generated galaxy catalog was then assembled using all the objects classified as galaxies in at least three filters. In all but one of the surveyed lines of sight, two exposures were taken in each passband; in those cases, "resolution" had to classify an object as a galaxy in both exposures for it to be declared a galaxy in that passband. This inclusive catalog contained 9,431 objects.

The second step was to use the IRAF package APPHOT to obtain aperture photometry of each object in the catalog described above. Each galaxy's flux was measured with concentric circular apertures ranging from 10 to 30 pixels (5".3 to 15".9) in diameter. Instrumental magnitudes and Poisson signal-to-noise were measured for each aperture; the sky value was computed separately for each object by taking the mode of the pixel values in an annulus around the aperture center, typically with inner diameter 32 pixels (17".0) and outer diameter 50 pixels (26".5).

An aperture optimization technique, similar to the growth curve optimization method used by Yee, Green & Stockman (1986), was then applied to each object. The function of the object's Poisson signal-to-noise vs. aperture radius was examined and the optimal size was determined to be either: (1) at the 30 pixel diameter (15".9) limit; or (2) where the next largest aperture showed an inflection point, indicating an intruding object or cosmic ray, or a decrease much larger than expected from the addition of random sky noise. The aperture size selection was performed using the R-band data, the passband with the greatest depth, for each object; extinction and color-corrected magnitudes were then extracted with the same aperture size in all six passbands.

The U-band magnitude selection limit for our blue galaxy sample was determined by our desire to have photometric errors of ~10% or less in all passbands for each galaxy. In the DMS, this meant a typical magnitude of U
≤ 21.1 for a galaxy with surface brightness levels typical of a Magellanic spiral. Visual inspection of the raw number counts, presented in Figure 1, shows that this is over a magnitude brighter than the U-band completeness limit of $U_{lim} \sim 22.2$; thus we are confident that such a selection limit would also be a complete, magnitude-limited sample.

To make sure all the galaxies within our magnitude limit would be included, we took the subset of all the objects in the inclusive survey brighter than $U=21.2$ – the magnitude limit desired, plus the typical 1σ photometric error at that limit – and inspected them visually. Using the IMEXAM task in IRAF, we checked that the automatically optimized aperture for each galaxy was indeed appropriate – that is, inclusive of all the galaxy light within the sky-limited isophotal magnitude, and not inclusive of nearby objects. Objects with stars or very large (>6 contiguous pixels) cosmic rays within the radius of our minimum aperture size (2″.6) were removed from the sample; these objects comprised about 5% (44 out of 953) of the original subsample. In cases where the aperture optimization algorithm was “deceived” (e.g., by a highly edge-on galaxy, or a strongly interacting system), the aperture size was adjusted appropriately.

The instrumental fluxes for the visually adjusted apertures were then extracted from the photometry database. Smaller, visually obvious cosmic rays in or near the apertures that were not removed in the initial calibration and reduction of the image frames (see HOGPW) were removed by hand using the FIXPIX task in IRAF, which replaces the affected pixels with a value interpolated from the surrounding pixels. Extinction and color-corrected magnitudes were again computed. In the lines of sight where two frames were available for each passband, a final additional check was made for cosmic rays and bad pixels: if the signal-to-noise of one image
in a given filter was more than 150% of the other image, it was assumed that a cosmic ray, chip defect or other systematic error was contaminating that image, and the uninflated measurement was used. Otherwise, the final magnitude for each bandpass was computed as a signal-to-noise weighted average of the two measurements. Finally, all the objects with $17.0 \leq U \leq 21.1$ were extracted. This subsample contains 667 objects, each of which has $\sim 10\%$ or better photometry in all six passbands.
REFERENCES


FIGURE CAPTIONS

Fig. 1 Total raw U-band galaxy number counts for the Deep Medium Survey. The dotted line at U=21.1 denotes the magnitude limit for the U-selected subsample.

Fig. 2 U-band number counts in the U-selected subsample (dark circles). Also plotted are the photographic U-band number counts of Koo (1986) and Jones et al. (1991).

Fig. 3 U-band number counts for the blue galaxies in the U-selected subsample, divided into low, medium and high-redshift bins.

Fig. 4 Luminosity functions constructed from the probability-weighted luminosity distributions of the blue galaxy subsample. The parameters of the Schechter function fits (dashed lines) are listed for each fit. The vertical axis is in units of log galaxies/magnitude/Mpc$^{-3}$.

Fig. 5 Luminosity function segments in the $0.15 \leq z < 0.30$ (squares) and $0.30 \leq z \leq 0.50$ (pentagons) redshift bins. The parameters of the Schechter function fits (dashed lines) are listed for each fit. The vertical axis is in units of log galaxies/magnitude/Mpc$^{-3}$. Open symbols denote magnitude bins affected by incompleteness.

Fig. 6 Absolute R magnitude vs. rest frame (U-R) color for the blue galaxy sample. The symbol for each galaxy denotes its location in the low (triangles), medium (squares) or high (circles) redshift bin.

Fig. 7 Histograms of (U-R) vs. galaxy number for the blue galaxy sample in three redshift bins and five absolute R magnitude bins. Each column contains galaxies in the same redshift bin, while each row contains galaxies in the same
magnitude bin.

**Fig. 8** Same as Figure 7, but with apparent magnitude limit reduced to $U \leq 20.8$ instead of 21.1.

**Fig. 9** Same as Figure 7, but with $(U-B)$ colors and absolute B magnitude bins.

**Fig. 10** The B-band luminosity function for the blue galaxies in the high-redshift bin, with all objects included (solid points) and with starbursting galaxies $(U-R<0.5)$ removed. The parameters of the Schecter function fits for each set of points are listed for each fit.
Figure F.2
Figure F.5
Figure F.6
Figure F.7
Figure F.8
Figure F.9
Figure F.10