# Stellar populations in Merging galaxies 

by

Anne Marie Turner

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

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## Acknowledgments

My deepest gratitude goes to my advisor, Rob Kennicutt. who encorraged me and stuck with me through the dark times as well as the light. I must thank him for his wisdom, and patience, and humor. He helped me find the strength, intelligence, and persistence within myself to finish what I started. He showed me by his example how to do research, and whenever I hear the word "scientist" my first thoughts are of him. To say this thesis would not have been possible without him is something of an understatement. There are not words.

Of course many others have made important contributions to this work, and other projects in my graduate career. This thesis work was carried out in collaboration with Hans-Walter Rix, who is quite possibly the smartest person I know. Two- and three-way brainstorming sessions between Rob, Hans, and myself greatly improved the quality of this thesis. Special thanks also goes out to Marcia Rieke, both for sitting on my thesis committee and for her efforts in my second-year project. I thank committee members Matthias Steinmetz and Abhijit Saha for taking the time to read this opus and provide comments which made it better. I also thank the HST Distance Scale Key Project team for allowing me to work on one of the "big" questions. And I must not forget Charles Peterson for helping me to get here in the first place.

The Steward staff has been wonderful about helping clean up all those little details. like where the money is coming from and keeping the computers working. Id like to thank all of them, especially Michelle Cournoyer, Joy Facio, and Alan Koski. I also thank John Waack, Vic Hanson, and especially Dennis Means, for making observing at the Steward $90^{\prime \prime}$ a productive and pleasant experience.

Finally I must thank my friends and family for helping to keep me sane. This list is long and I'm sure to forget someone, but ['ll give it a shot. Office mates Dante, Julio, Nadine, and Greg made life at Steward a little more pleasant. I commiserated and rejoiced with fellow grad students Kim, Brian, Sally, Lisa, Pat. Eric, Peter, Evonne, Milagros, Tim, Chad, and Craig. Donice, Jim, Sue, and Alan helped me remember that there was a real world outside the dome. And very special thanks go to Ruth Kineale, Sherry Baer, and of course my family Paul \& Rita Turner, and Jenny Ernst. And my love to Doug, for many reasons, but especially for telling me it was OK to be scared.

This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This work was supported by NSF Grant $94-21145$. I gratefully acknowledge partial support of an NSF Graduate Fellowship. I thank G. Bruzual, S. Charlot, M. Fioc, and B. Rocca-Volmerange for making the GISSEL96 and PEGASE EPS models available online.

## Dedication

There are two bequests
That we can give our children.
One is roots,
The other is wings.

I dedicate this work to my parents, with love.

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#### Abstract

To examine the stellar populations of interacting or merging galaxies, a sample of 28 objects with disturbed morphology was selected. Integrated spectra of these galaxies were obtained, to study their global star formation histories and provide a database for comparison with morphologically disturbed galaxies at high redshift. Quantitative star formation histories were determined using evolutionary population synthesis models. Special emphasis was placed on observational and systematic uncertainties, e.g. IMF, metallicity, and reddening. The merger sample was divided into two subsamples for comparison with morphologically normal galaxies. The red subsample consists of galaxies whose spectra resemble those of early-type galaxies, while the blue subsample has moderate to strong $\mathrm{H} \alpha$ emission.

The model fits to the spectra of the red merger sample are indistinguishable from those in a control sample of S0 galaxies. Differences in the upper limits on recent star formation between these mergers and a sample of elliptical galaxies may be due to metallicity effects. The minimum amount of star formation required in the last Gyr is consistent with zero for the red merger and the E/S0 samples. The maximum amount of new star formation ranges from $0.2-3.2 \%$ by mass in the merger sample and $0.0-2.7 \%$ in the $\mathrm{E} / \mathrm{S} 0$ control sample.

Reddening contributes the largest source of uncertainty in determining the mass of a starburst in the blue merger subsample, while burst ages are relatively unaffected. We put limits on the quantitative star formations histories in these galaxies, although the uncertainties tend to be large. We find starbursts ranging in


age from $10^{7}$ to $10^{9}$ years, and burst masses from 0 to more than $20 \%$ of the total stellar mass. We find higher recent rates of star formation in the merger sample based on far-infrared luminosities and Balmer absorption strengths, respectively. We cannot distinguish between truncated star formation followed by a starburst, and alternate star formation histories, such as those appropriate to spiral-type star formation, based on our model fits alone. A Salpeter [MF appears to be an adequate one to describe star formation in these galaxies.

## Chapter 1

## Introduction

A merger or gravitational interaction between galaxies, in addition to radically changing the morphology and kinematics of a galaxy, can make a significant change in these galaxies' stellar populations (e.g. Kennicutt 1998). The merger hypothesis for the formation of elliptical galaxies states that when two disk galaxies merge. they form an elliptical galaxy (Toomre 1977). The stellar populations that make up present day elliptical and spiral galaxies are quite different: a spiral galaxy contains a mixed population of young and old stars and a significant mass fraction in cold gas, while an elliptical galaxy has stellar populations that appear to be uniformly old and relatively free of cold gas. If the merger hypothesis is correct, the resulting change that occurs in a galaxy's stellar populations as a result of a merger may be quite dramatic, especially in the case of a merger of a gas-rich spiral.

In fact, mergers are observed to cause spectacular bursts of star formation. Ultraluminous infrared galaxies (ULIRGs), have morphologies indicative of an ongoing merger event, almost without exception (Sanders \& Mirabel 1996). HST has provided astronomers a view of very young star clusters, possibly young
globular clusters, in the mergers NGC 7252 (Whitmore et al. 1993), NGC 4038/9 (Whitmore \& Schweizer 1995) and NGC 3921 (Schweizer et al. 1996), which are likely to be the result of intense, merger-induced star formation. However, in spite of spectacular star bursts like these, in nearly every morphologically selected sample of interacting galaxies and mergers, a considerable fraction of the galaxies show little or no star formation. Some of the interacting galaxies in the Larson \& Tinsley (1978) sample show colors like those of normal galaxies. Bernlöhr (1993a) classifies a large fraction of his sample of interacting galaxies as having spectra like those of early-type galaxies, and mergers with such spectra are also clearly present in the Liu \& Kennicutt (1995b, hereafter LK95) sample.

Quantitative analyses of the stellar populations in merging and interacting galaxies have been made primarily by two methods, the application of evolutionary population synthesis (EPS) codes to examine the star formation histories of interacting galaxies, and measurement of ongoing star formation through galaxy emission line studies. In addition. multicolor imaging has been useful in mapping out the locations of the stellar populations within galaxies.

EPS codes have been instrumental in interpreting observations of mergers since the pioneering work of Larson \& Tinsley (1978), who compared the star formation histories of mergers and interacting galaxies to those of morphologically normal galaxies. They found that while the normal galaxies' UBV colors were consistent with a monotonically decreasing star formation rate (SFR), the morphologically peculiar interacting galaxies often needed a recent burst of star formation to explain their colors. More recently, EPS models have been used to fit the optical spectra of interacting, merging, and early-type galaxies to learn more about the detailed star formation histories of individual galaxies (Bernlöhr 1993a, Fritze-von

Alvensleben \& Gerhard 1994, and Schweizer \& Seitzer 1992, respectively). Bernlöhr found some evidence for an initial mass function (IMF) weighted toward high mass stars in his sample of interacting galaxies and a time delay in star formation in the larger galaxy of an interacting pair, relative to the smaller. Fritze-von Alvensleben $\&$ Gerhard were able to examine the star formation history of the prototypical merger, NGC 7252 (Schweizer 1982), in great detail, finding a 1.3 Gyr old star burst which could account for $20-50 \%$ of the galaxy's stellar mass. Schweizer \& Seitzer determined heuristic merger ages for samples of E and S 0 galaxies and found a correlation between those ages and (presumably) merger induced morphological fine structure. EPS models have also been applied to merging and interacting galaxies along with morphologically normal galaxies in studies of star burst galaxies (e.g. Englebracht 1997, Shier et al. 1996).

Emission line studies have also been valuable in understanding the stellar populations in interacting galaxies. Bushouse (1987) and Kennicutt et al. (1987) showed that even relatively weak gravitational interactions between galaxies could enhance star formation, since pairs of disk galaxies. even without morphological signs of interaction, had systematically higher SFRs than isolated disk galaxies. Star formation at the present epoch has also been examined in more detail for a sample of more strongly interacting galaxies and merger candidates by Sekiguchi \& Wolstencroft (1993). They found that these galaxies had enhanced star formation compared to isolated disk galaxies. They also suggested that the mixture of $\mathrm{H} \alpha$ emission with Balmer absorption seen in many merging galaxies might indicate recurrent star bursts or propagating star formation. Liu \& Kennicutt (1995a) examined the emission line properties of a sample of mergers and interacting galaxies with similar results. They also found the spectra of their sample appeared much like many samples of galaxies observed at higher redshift. Donzelli \&

Pastoria (1997) studied pairs of galaxies, each pair consisting of galaxies of different sizes. They found $\mathrm{H} \alpha$ emission was enhanced in the both galaxies in the interacting pairs, more strongly so in the smaller galaxy of such pairs. Hibbard and van Gorkom (1996) used H $\alpha$ imaging of a sequence of mergers to show that star formation begins in the disks of the interacting galaxies, and moves to the nucleus as the merger proceeds.

Multicolor imaging has also added to our knowledge of the stellar populations in mergers. Schombert et al. (1990) made a four color study of interacting galaxies and found large color variations within each system. They concluded that very blue colors of the tidal features in many of these galaxies were indicative of recent star formation while those in other galaxies were similar in color to the outer parts of spiral galaxies, and therefore likely to be tidally stripped. McGaugh \& Bothun (1990) performed surface photometry of three shell galaxies. One galaxy. IC 51, was found to have shells made of young material, another, NGC 758.5, had shells likely to be stripped material from a spiral galaxy, and a third, NGC 7010. was puzzling with shells even redder than the underlying elliptical galaxy. Smith \& Hintzen (1991) performed multicolor photometry of a sample of mergers and found a wide range of colors, from those redder than a typical elliptical galaxy to extremely blue. They also saw contrasting colors in interacting pairs perhaps indicating differing star formation in the two galaxies.

Theoretical modeling of the interaction-induced star formation in interacting galaxies has become feasible in recent years with the coupling of N-body and hydrodynamic codes. Hernquist (1989) and Barnes \& Hernquist (1991) showed that gas was driven to the center of the remnant as two gas-rich galaxies merged. Mihos et al. $(1992,1993)$ using a modified Schmidt (1959) star formation law and
a discrete cloud model rather than a full hydrodynamics code, showed that star formation rates in mergers could increase by an order of magnitude for timescales of a few $\times 10^{8} \mathrm{yr}$, and that these models could reproduce the star formation intensity and spatial distribution in five merger remnants. Again using a full N-body, hydrodynamic code. Mihos \& Hernquist (1994a) showed that the presence of a bulge suppresses radial inflow of gas in a minor merger, delaying a star burst until the merger is nearly complete. This also holds true for major mergers (Mihos \& Hernquist 1994b), where the resulting star burst can easily reach the ULIRG range. For either type of merger where bulgeless galaxies are involved. starbursts occur much earlier in the interaction, and gas is exhausted before the galaxy nuclei merge. Mihos \& Hernquist (1996) also showed that progenitor galaxy structure plays the dominant role in regulating star formation, with an increase in the star formation rate of up to two orders of magnitude over the pre-merger rate. Up to $75 \%$ of the gas in the progenitors may flow in to the nucleus of the merger remnant for such a scenario.

In spite of the extensive progress made in this previous work, many unanswered questions remain. From the literature review above, it is clear that the star formation histories of mergers have been studied in detail in only a few isolated galaxies, like the well-studied NGC 7252 , while surveys of large groups of galaxies have focused on the current rates of star formation, primarily through $\mathrm{H} \alpha$ emission. A quantitative estimate of the star formation history for each galaxy of a large sample of mergers is needed. How much of their optical light is contributed by an interaction-induced star burst, and how much stellar mass is involved? How old are the star bursts we do see? What limits can we put on these quantities? With these results in hand we can address still more unanswered questions. Do star bursts occur in all interacting galaxies? How much variation in stellar populations
is there between mergers? Does the star formation history correlate with galaxy morphology, gas or dust content? How do the stellar populations in mergers compare with morphologically normal galaxies? Do mergers leave a spectral signature which could be found in a "normal" galaxy that might grow out of the merger remnant?

The answers to these questions are more important than ever. Galaxy interactions are now thought to play a crucial role in galaxy evolution. Mergers have been called on to explain such phenomena as the disappearance of the "faint blue galaxies" seen at high redshift (e.g. Colless et al. 1993) and the increase in "blue" or "active" galaxies in moderate redshift clusters (the Butcher-Oemler effect; e.g. Lavery et al. 1992, Dressler et al. 1994, Kauffmann 199.5). Hubble Space Telescope imaging of high redshift clusters, the Hubble Deep Field, and Medium Deep Survey has shown that disturbed morphology is much more common at high redshift (e.g. Oemler et al. 1997. van den Bergh et al. 1996, and Neuschaefer et al. 1997, respectively). Interpreting the observations of high-redshift objects can be aided by clearly understanding what is happening with mergers and interacting galaxies in the local universe.

The goal of this thesis is to answer the questions outlined above, and to create a base of information, both for understanding local mergers in their own right, and for use in interpreting the observations of high-redshift interacting galaxies. We have undertaken a program to study in detail the stellar populations of a large, morphologically-selected sample of 28 systems, comprising all types of interacting galaxies and mergers, with current star formation rates from almost zero to the ULIRG range. We measure the masses and ages of the star bursts in our sample by comparing their spectra to synthetic stellar population synthesis spectra. We
subdivide the complete merger sample into blue and red subsamples for purposes of comparison with morphologically normal $\mathrm{E} / \mathrm{S} 0$ and spiral control galaxies. to distinguish between normal and interaction-induced star formation modes.

In this thesis, we concentrate on measuring the global star formation in a galaxy, without regard to its spatial distribution. The reason for this is two-fold; first, to measure the total amount of star formation. which may not be limited to the galaxy nucleus or any other specific region, and second, for purposes of comparison to the high-redshift objects where mergers are thought to play a role and for which spatially-resolved spectra are not generally available. One limitation of existing merger spectra is restricted spatial coverage, usually biased to the nuclear region of the galaxy. For these reasons, we perform our analysis on integrated spectra of the galaxies in our sample, so the global properties can be measured. The spatial distribution of the stellar populations in mergers is an interesting question in its own right. but beyond the scope of this thesis.

This thesis is structured as follows. In Chapter 2, we describe the sample selection and observing and data reduction procedures. Chapter 3 contains a description of the models and fitting procedure we use to analyze the stellar populations in our sample, as well as tests made of these models and procedures. We present and interpret our results for the red subsample in Chapter 4 and the blue subsample in Chapter 5. In Chapter 6. we conclude with a summary of our main results and suggestions for future work.

## Chapter 2

## The Data

Integrated spectra were acquired for a morphologically-selected sample of interacting galaxies. These were supplemented with previously published spectra of morphologically normal galaxies for use as a control sample.

### 2.1. Sample Selection

We constructed a morphologically-selected sample of strongly interacting and merging galaxies. drawn from the Arp atlas (1966). and similar to the sample in Liu \& Kennicutt (199.5b. hereafter LK9.5). Where possible. we consulted LK9.5 to be sure our sample was spectroscopically representative as well. Galaxies that showed evidence for strong interaction or recent merging in the form of tidal tails. bridges, or strong shells were selected. Shell galaxies were included since shell formation may result from a major merger (Hernquist \& Spergel 1992) and are not strictly the result of a minor merger (Hernquist \& Quinn 1988). We have divided this into two subsamples for purposes of comparing with relevant control samples of morphologically normal galaxies. The galaxies in the red subsample
have spectra that show no or very weak line emission and have continua strongly resembling those of elliptical galaxies. The galaxy spectra of blue subsample have prominent $\mathrm{H} \alpha$ emission and typically bluer stellar continua. This division is somewhat artificial as there is a smooth progression from blue to red in the entire sample, and some galaxies, such as NGC 3303, might have equally well been placed in either subsample.

The red subsample consists of three pairs of interacting galaxies (NGC $7.50 / 1$. NGC 942/3, NGC 7284/5), three shell galaxies (IC 162, NGC 474, NGC 7585), and one galaxy with tidal tails and extremely disturbed morphology (NGC 7727 ). We refer to this subsample as the red merger sample throughout this thesis. Figures 2.1 and 2.2 show $V$-band images of these galaxies, taken at the Steward 2.3 m telescope on Kitt Peak.

To compare with the red mergers, we also make use of a control sample of elliptical and S0 galaxy integrated spectra from the Kennicutt (1992b, hereafter K92) spectral atlas. This sample was chosen since it is one of the few sources of integrated spectra of galaxies with a wide range of morphological types in the literature, including four elliptical and four S 0 galaxies. The purpose of using this control sample is to perform a differential analysis, rather than setting absolute limits on the star formation of both samples. The possible presence of young stars in ellipticals has been the subject of much investigation in its own right (e.g. Charlot et al. 1996), and our analysis adds only a limited amount of new information to that discussion. The galaxies in the red merger and E/SO control samples are listed in Table 2.1 along with their heliocentric recessional velocity, absolute magnitude, Mg2 index, neutral hydrogen mass, and distance. Only two of the red galaxies are listed as IRAS sources in Cataloged Galaxies \& Quasars
(1989). These are the S0 galaxies NGC 3245 and NGC 5866 with $\log L_{F I R}$ equal to 9.11 and $9.28 \log L_{\odot}$, respectively, when corrected to their tabulated distances.

The blue subsample consists of 18 galaxies for which we have acquired spectra. plus integrated spectra of NGC 1222, Arp 220, and NGC 7252 from LK95 for a total of 21 galaxies. Five of these, NGC 4038/9, NGC 4676, NGC 5278/9, Arp 241, and NGC 6621/2 are strongly interacting pairs (not evolved mergers), while one other, Arp 195, is a strongly interacting triplet. For convenience, we refer to this subsample as the blue merger sample throughout this thesis. Several of these galaxies have been identified as having AGN: NGC 3921 (Dahari 198.5). NGC 5278/9 and NGC 4676 (Keel et al. 1985), Arp 220 and NGC 2623 (Shier 1995), and Arp 195, NGC 3303, and possibly NGC 3656 (Liu \& Kennicutt 199.5a).

Figures 2.3 through 2.5 show $V$-band images of these galaxies, taken at the Steward 2.3 m telescope on Kitt Peak. For IC 51, NGC 520, NGC 4038/9. Arp 241, and NGC 7252 , see $\operatorname{Arp}$ (1966) objects 230 . 157. 244. 241. and 226 , respectively.

To compare with the blue mergers, we make use of the spiral galaxies from the K92 spectral atlas. Again, these control galaxies were selected on the basis of their morphology and not their star formation rates or history, i.e. some starburst galaxies are included in the control sample. The galaxies in the blue merger and spiral control samples are listed in Tables 2.2 and 2.3. along with their heliocentric recessional velocity, absolute magnitude, neutral hydrogen mass, and distance.

### 2.2. Observations and Data Reduction

Observations of the red merger sample were made with the Boller and Chivens (B\&C) Spectrograph on the Steward Observatory 2.3m telescope at Kitt Peak. A $\log$ of observations is presented in Table 2.4. The detector was a thinned $1200 \times 800$

Loral CCD, with a spatial scale of $0.8 / 8 /$ pixel. A $400 \mathrm{I} / \mathrm{mm}$ grating, blazed at 4889 $\AA$ was used with a UV- 36 blocking filter to obtain a spectra over the wavelength range, $3600-6900 \AA$. A $2 \cdot 5$ slit yielded a resolution of approximately 7.5 A. Integrated spectra were obtained using the drift-scanning technique, detailed in K92. Briefly, each galaxy was allowed to drift across the slit several times during an exposure, thus creating an effective total aperture with length equal to the length of the scan. The apertures are listed in column 6 of Table 2.4 as arcseconds in right ascension by arcseconds in declination, except as noted. Drift rates were adjusted so each galaxy was scanned across the slit at least 6 times during a 30 minute exposure. Scans were generally performed in the shorter aperture direction to increase signal-to-noise, since slower drift rates effectively spend more time on the galaxy. Two to four separate exposures were acquired for each galaxy, to keep the number of cosmic ray hits to acceptable levels. All drift-scan observations were made under photometric conditions.

The spectral images were reduced with IRAF using standard techniques. Each image was cleaned of bad pixels and columns, overscan corrected and bias subtracted. Dark frame corrections were applied when the number of dark counts was found to be non-negligible compared to the CCD read noise. Special care was taken in flat-fielding the data. First, a response function was created by removing a high order polynomial from the dome flats. This response function was then divided into a twilight flat. An illumination correction was made by fitting a high order function along the spatial direction of this twilight flat in each of several (typically 20 ) bins. A composite flat field was created by multiplying the response function by the illumination correction, and was then used to flatten the spectral images.

Galaxy spectra were extracted interactively, using the observed intensity profile along the slit to determine apertures and background regions, and then fitting a trace to the observed spectrum. Wavelength calibrations were determined using HeAr and FeNe lamps. Standard stars from Massey et al. (1988) were observed with a 4.5 slit aligned to the parallactic angle, and were used to calibrate the spectrophotometry. The wide slit was used to minimize calibration errors introduced by the wavelength-dependent seeing. Spectra from separate exposures of the same galaxy were then averaged to produce the final integrated spectrum. These integrated spectra typically have $\mathrm{S} / \mathrm{N} \sim 50$. The resulting integrated spectra for the merger sample are shown in Figures 2.6-2.9.

The integrated spectra were compared to nuclear spectra from the LK95 atlas. By examining the qualitative differences, and using the images as a rough guide, we determined that in only three cases were the integrated spectra dominated by the light from the nucleus of the system. These three cases were NGC 122.2. Arp 241, and NGC 4194.

Errors in the spectrophotometry are dominated by calibration uncertainties and sky subtraction errors. Residuals from the mean calibration of the standard stars were $2.5 \%$ or less, but the spectrophotometry of the galaxies. taken in a much larger effective aperture, may be less precise, largely due to increased sky subtraction uncertainties. We were able to test the spectrophotometry by comparing spectra of the same galaxy taken on different nights, and those galaxies common to our merger sample those of K92 or LK95. Comparison of spectra between these data sets is shown in Figure 2.10. Spectrophotometry taken on different nights shows a maximum peak-to-peak variation of $\pm 7.5 \%$, with a typical value of $\pm 5 \%$. This variation is linear from the blue to the red ends of the
spectrum, i.e. a difference of $+5 \%$ at the red end, $-5 \%$ at the blue. and a smooth gradient in between. Comparison of galaxy spectrophotometry from the K 9 . and LK9.5 shows typical peak-to-peak variations of $\pm 6 \%$, with a maximum variation of $\pm 10 \%$. However, in these comparisons, the pattern of variation often changes near $5150 \AA$, where the blue and red ends of the K92 and LK95 spectra were spliced together. This indicates that some of the variation may be due to calibration error introduced by that process. We also note these comparisons reflect the maximum errors over broad wavelength ranges in any given spectrum; the RMS variations are about 2-3 times lower.

Spectrophotometric errors may also be introduced by imperfect sky subtraction. These do not constitute a significant source of error in the analysis that follows. which makes use of the entire galaxy spectrum, so we simply interpolated over regions of poor sky line subtraction. However, measures of equivalent width or spectral indices may indeed have significant error when falling on or near a night sky line.

Table 2.1. Red Galaxy Properties

| Galaxy | $c z\left(\mathrm{~km} \mathrm{~s}^{-1}\right)$ | $M_{B}{ }^{\text {a }}$ | $\mathrm{Mg} 2^{\text {b }}$ | $\mathrm{M}_{\mathrm{HI}}\left(\mathrm{M}_{6}\right)^{\mathrm{c}}$ | $D(\mathrm{Mpc})^{\text {d }}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Red Merger Sample |  |  |  |  |  |
| IC 162 | 5132 | -20.8 | 0.22 | $2.0 \times 10^{9}$ | 80.7 |
| NGC 474 | 2372 | -21.6 | 0.22 | $1.1 \times 10^{9}$ | 37.5 |
| NGC 750/1 | 529.3 | $-21.7$ | 0.25 | $2.0 \times 10^{9}$ | 81.6 |
| NGC 942/3 | 4439 | $\ldots$ | 0.18 | $\ldots$ | 72.4 |
| NGC 7284 | 4527 | $-21.3$ | 0.22 |  | 70.8 |
| NGC 728.5 | 452 | -21.4 | 0.2 |  | 70.8 |
| NGC 758.5 | 3447 | -21.1 | 0.18 | $<1.1 \times 10^{10}$ | 53.9 |
| NGC 7T27 | 19.53 | -20.8 | 0.22 | $7.3 \times 10^{8}$ | 29.7 |
| Elliptical Galaxies |  |  |  |  |  |
| NGC 3379 | 920 | -20.2 | 0.22 | $<6.3 \times 10^{6}$ | 12.2 |
| NGC 4472 | 868 | -21.8 | 0.25 | $<9.0 \times 10^{6}$ | 16.8 |
| NGC 4648 | 1472 | $-19.5$ | 0.24 | $\cdots$ | 25.6 |
| NGC 4889 | 6494 | -22.6 | 0.28 | $<1.3 \times 10^{9}$ | 100. |
| S0 Galaxies |  |  |  |  |  |
| NGC 3245 | 13.56 | -19.8 | 0.18 | $<6.8 \times 10^{7}$ | 20.0 |
| NGC 3941 | 928 | $-19.5$ | 0.22 | $8.0 \times 10^{8}$ | 14.7 |
| NGC 4262 | 13.59 | -18.9 | 0.27 | $5.5 \times 10^{8}$ | 16.8 |
| NGC 5866 | 672 | -19.5 | 0.17 | $<2.2 \times 10^{8}$ | 13.2 |

${ }^{\text {a }}$ derived from de Vaucouleurs et al. (1991). $\mathrm{H}_{0}=65 \mathrm{~km} \mathrm{~s}^{-1} \mathrm{Mpc}^{-1}$
${ }^{\mathrm{b}}$ calculated from integrated spectra as defined Faber et al. (1985)
'from the compilation of Roberts et al. (1991), except IC 162 (Hutchings 1989) and NGC $750 / 751$ (Huchtmeier 1994). All values are on the Roberts et al. system, and corrected to $\mathrm{H}_{0}=65 \mathrm{~km} \mathrm{~s}^{-1} \mathrm{Mpc}^{-1}$
${ }^{\mathrm{d}} D=\left(V_{H}+300 \sin l \cos b\right) / H_{0}$, as in Roberts et al. 1991.

Table 2.2. Blue Galaxy Properties-Mergers

| Galaxy | $\begin{gathered} c z \\ \left(\mathrm{~km} \mathrm{~s}^{-1}\right) \end{gathered}$ | $\begin{gathered} M_{B}^{a} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} \mathrm{M}_{\mathrm{HI}}^{b} \\ \left(10^{9} \mathrm{M}_{6}\right) \end{gathered}$ | $\begin{aligned} & \log L_{F I R}{ }^{c} \\ & \left(\log L_{6}\right) \end{aligned}$ | $\begin{gathered} \mathrm{D}^{\mathrm{d}} \\ (\mathrm{Mpc}) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| IC 51 | 1675 | $\ldots$ | 1.56 | 9.43 | 26.7 |
| NGC 520 | 2281 | -20.0 | 8.07 | 10.82 | 36.7 |
| NGC 523 | 4761 | $-19.5$ | 22.8 | 10.34 | 76.3 |
| NGC 122) | 2452 | -21.3 | 3.17 | 10.41 | 37.6 |
| NGC 1614 | 4778 | -20.6 | $>3.67$ | 11.36 | 71.4 |
| NGC 2623 | 5535 | -20.6 | 2.33 | 11.38 | 83.9 |
| Arp 195 | 16758 | $-2.5$ | ... | 11.40 | 257. |
| NGC 2782 | 2562 | -21.0 | 5.61 | 11.32 | 39.3 |
| NGC 3303 | 6165 | ... | 3.67 | ... | 93.2 |
| NGC 3448 | 13.50 | -19.7 | 6.33 | 9.67 | 22.0 |
| NGC 3656 | 2869 | -20.0 | 1.16 | 9.96 | 45.4 |
| NGC 3921 | 5838 | -21.6 | 11.1 | 10.08 | 91.3 |
| NGC 4038/9 | 1641 | $-21.5$ | 3.93 | 10.52 | 22.0 |
| NGC 4194 | 2506 | -20.0 | 1.59 | 10.73 | 40.1 |
| NGC 4676 | 6610 | ... | 10.1 | 10.65 | 102. |
| [C 88:3 | 7000 | -20.8 | < 4.0 | 11.45 | 108. |
| NGC 5278/9 | 7463 | ... | 5.52 | 10.72 | 117. |
| Arp 241 | 10401 | $\cdots$ | 7.8:3 | ... | 161. |
| Arp 220 | 5434 | -21.1 | 36.3 | 12.04 | 8.5 .3 |
| NGC 6621/2 | 6230 | -20.9 | 10.5 | 11.04 | 99.3 |
| NGC 72.52 | 4688 | $-21.7$ | 5.08 | 10.54 | 73.3 |

${ }^{\text {a }}$ derived from de Vaucouleurs et al. (1991). except NGC 6621/2 from de Vaucouleurs et al. (1976). Assumes $\mathrm{H}_{0}=65 \mathrm{~km} \mathrm{~s}^{-1} \mathrm{Mpc}^{-1}$.
${ }^{\mathrm{b}}$ from the compilation of Huchtmeier \& Richter (1989) except IC $51 \&$ IC 883 from Huchtmeier (1997), NGC 523 from Wegner et al. (1993), and NGC 7252 from Hibbard et al. (1994). All values are corrected to $\mathrm{H}_{0}=65 \mathrm{~km} \mathrm{~s}^{-1} \mathrm{Mpc}^{-1}$.
${ }^{\text {cf from Cataloged Galaxies and Quasars, } 1989 . ~}$
${ }^{\mathrm{d}} D=\left(V_{H}+300 \sin l \cos b\right) / H_{0}$.

Table 2.3. Blue Galaxy Properties-Spiral Control Sample

| Galaxy | Type | $\begin{gathered} c z \\ \left(\mathrm{~km} \mathrm{~s}^{-1}\right) \end{gathered}$ | $\begin{gathered} M_{B}^{a} \\ (\mathrm{mag}) \end{gathered}$ | $\begin{gathered} \mathrm{M}_{\mathrm{HI}}^{b} \\ \left(10^{9} \mathrm{M}_{\mathrm{C}}\right) \end{gathered}$ | $\begin{gathered} \log \mathrm{L}_{F I R}{ }^{\mathrm{c}} \\ \left(\log \mathrm{~L}_{G}\right) \end{gathered}$ | $\begin{gathered} \mathrm{D}^{\mathrm{d}} \\ (\mathrm{Mpc}) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| NGC 1357 | Sa | 2009 | -19.9 | $<1.3$ | 9.41 | 29.9 |
| NGC 2275 | Sa | 1354 | -20.2 | 0.48 |  | 18.2 |
| NGC 3623 | Sa | S07 | -20.1 | 0.38 | 8.90 | 10.6 |
| NGC 3368 | Sab | S97 | -20.4 | 2.9 | 9.43 | 11.8 |
| NGC 1832 | SBb | 1937 | $-19.7$ | 4.3 | 9.99 | 27.4 |
| NGC 3147 | Sb | 2820 | -21.9 | 12. | 10.52 | 45.8 |
| NGC 3627 | Sb | 727 | $-20.3$ | 0.91 | 9.81 | 9.4 |
| NGC 47.50 | Sb pec | 1618 | -20.1 | 2.2 | 9.87 | 27.7 |
| NGC 5248 | Sbc | 1153 | -20.6 | 6.4 | 9.99 | 17.1 |
| NGC 6217 | SBbc | 1362 | -19.9 | 7.8 | 10.04 | 24.5 |
| NGC 2276 | Sc | 2410 | -20.8 | 8.1 | 10.57 | 40.3 |
| NGC 2903 | Sc | 5.56 | -19.6 | 3.1 | 9.52 | 7.0 |
| NGC 4631 | Sc | 606 | $-20.3$ | 13. | 9.93 | 9.6 |
| NGC 477.5 | Sc | 1.567 | -20.0 | 3.3 | 9.56 | 22.0 |
| NGC 6181 | Sc | 2375 | -20.3 | 8.2 | 10.40 | 38.7 |
| NGC 6643 | Sc | 1489 | -20.2 | 6.0 | 10.20 | 26.8 |
| NGC 1.569 | Sm/Im | -104 | -16.1 | ... | 8.9:3 | 3.6 |
| NGC 4449 | $\mathrm{Sm} / \mathrm{Im}$ | 207 | $-17.9$ | 1.9 | ... | 4.1 |
| NGC 4485 | $\mathrm{Sm} / \mathrm{Im}$ | 493 | $-17.2$ | 5.5 | $\ldots$ | 8.4 |
| NGC 4670 | SB pec | 1069 | $-18.2$ | 0.61 | 9.04 | 16.4 |
| M 82 | 10 | 203 | $-18.5$ | 2.1 | 9.21 | 3.6 |

${ }^{\text {a }}$ derived from de Vaucouleurs et al. (1991). $\mathrm{H}_{0}=65 \mathrm{~km} \mathrm{~s}^{-1} \mathrm{Mpc}^{-1}$
${ }^{\mathrm{b}}$ from the compilation of Huchtmeier \& Richter (1989). All values are corrected to $\mathrm{H}_{0}=65 \mathrm{~km} \mathrm{~s}^{-1} \mathrm{Mpc}^{-1}$.
${ }^{\text {cfrom Cataloged Cralaxies and Quasars, } 1989 .}$
${ }^{\mathrm{d}} D=\left(V_{H}+300 \sin l \cos b\right) / H_{0}$, except NGC 1.569 from the IC $342 / \mathrm{Maffei}$ group distance by Krisner et al. (1995), and M82 from the M81 distance by Freedman et al. (1994).

Table 2.4. Log of Observations

| galaxy | Arp\# | $c z\left(\mathrm{~km} \mathrm{~s}^{-1}\right)$ | date | $\exp (\mathrm{s})$ | ap(" ${ }^{\prime \prime}$ ") |
| :---: | :---: | :---: | :---: | :---: | :---: |
| IC 51 | 230 | 1758 | 11/28/94 | 5400 | $38 \times 89$ |
| NGC 474 | 227 | 2372 | 10/18/9.5 | 5400 | $60 \times 138$ |
| NGC 520 | 157 | 2244 | 10/17/95 | 5400 | $1.55 \times 100$ |
| NGC 523 | 158 | 4761 | 10/17/9.5 | 5400 | $96 \times 30$ |
| NGC 750/1 | 166 | 5293 | 11/28/94 | 3600 | $106 \times 30$ |
| NGC 942/3 | 309 | 4439 | 11/28/94 | 3600 | $33 \times 125$ |
| IC 162 | 228 | 5132 | 10/18/9.5 | 5400 | $40 \times 133$ |
| NGC 1614 | 186 | 4745 | 10/17/95 | 5400 | $25 \times 79$ |
| NGC 2623 | 243 | 5508 | 3/26/9.5 | 5400 | (a) |
| Arp 195 | 195 | 17302 | 4/10/97 | 5400 | $16 \times 84$ |
| NGC 2782 | 21.5 | 2562 | 10/18/95 | . 5400 | $129 \times 60$ |
| NGC 3303 | 192 | 62.55 | $3 / 27 / 9.5$ | . 5400 | $69 \times 30$ |
| NGC 3448 | 20.5 | 1360 | 4/10/97 | 3600 | (b) |
| NGC 3656 | 1.5 | 28.53 | 3/26/95 | 5400 | $40 \times 111$ |
| NGC 3921 | $2 \cdot 24$ | 589.5 | 3/26/95 | $3600{ }^{=}$ | $94 \times 20$ |
| NGC 4038/9 | 244 | 1499 | 3/27/95 | 5400 | $191 \times 16.5$ |
| NGC 4194 | 160 | 2610 | 3/27/9.5 | . 3400 | (c) |
| NGC 4676 | 242 | 6610 | 4/10/97 | 3600 | $90 \times 1.50=$ |
|  |  |  | 4/10/97 | 1800 | $50 \times 1.55=$ |
| IC 88:3 | 193 | 6894 | 3/26/9.5 | 7200 | (d) |
| NGC 5278/9 | 239 | 7.585 | 3/27/95 | 5400 | $111 \times 42$ |
| Arp 241 | 241 | 10380 | 4/22/96 | 3600 | ( $\epsilon$ ) |
| NGC 6621/2 | 81 | 6490 | 10/17/9.5 | 5400 | $60 \times 122$ |
| NGC 7284/5 | 93 | 1991 | 10/18/95 | 5400 | $70 \times 132$ |
| NGC 7.585 | 223 | 3447 | 10/18/95 | . 5400 | $130 \times 60$ |
| NGC 7727 | 22. | 19.53 | 10/17/95 | 5400 | $149 \times 100$ |

*Spectrum acquired in 31200 second exposures.
=-Spectra from these apertures were indistinguishable and so were summed.
Apertures are rectangular except as noted. Non-rectangular apertures (a)(e) are defined by length of slit used, position angle of slit. length of drift scan. and direction of scan (either right ascension or declination). (a) $87^{\prime \prime}, 60^{\circ}, 40^{\prime \prime}$. $\delta$. (b) $162^{\prime \prime}, 70^{\circ}, 60^{\prime \prime}$, $\delta$. (c) $125^{\prime \prime}, 15^{\circ}, 30^{\prime \prime}, \alpha$. (d) $130^{\prime \prime}, 130^{\circ}, 20^{\prime \prime}$, $\delta$. (e) $74^{\prime \prime}$. $143^{\circ}, 25^{\prime \prime}, \delta$.


Figure 2.1 $V$-band images of the red merger subsample, taken with the Steward Observatory 2.3 m telescope on Kitt Peak. North is up and east to the right. The horizontal bar represents a projected distance of 10 kpc at the distance of the galaxy given in Table 2.1. Scaling is logarithmic to show detail.


Figure $2.2 V$-band images of the red merger subsample, taken with the Steward Observatory 2.3 m telescope on Kitt Peak. North is up and east to the right. The horizontal bar represents a projected distance of 10 kpc at the distance of the galaxy given in Table 2.1. Scaling is logarithmic to show detail.


Figure 2.3 V -band images of the blue merger subsample, taken with the Steward Observatory 2.3 m telescope on Kitt Peak. North is up and east to the right. The horizontal bar represents a projected distance of 10 kpc at the distance of the galaxy given in Table 2.2. Scaling is logarithmic to show detail.


Figure 2.4 $V$-band images of the blue merger subsample, taken with the Steward Observatory 2.3 m telescope on Kitt Peak. North is up and east to the right. The horizontal bar represents a projected distance of 10 kpc at the distance of the galaxy given in Table 2.2. Scaling is logarithmic to show detail.


Figure 2.5 V -band images of the blue merger subsample, taken with the Steward Observatory 2.3 m telescope on Kitt Peak. North is up and east to the right. The horizontal bar represents a projected distance of 10 kpc at the distance of the galaxy given in Table 2.2. Scaling is logarithmic to show detail.


Figure 2.6 Integrated spectra of the red merger subsample obtained by the drift scanning technique. $F_{\lambda}$ is normalized to the mean value for the spectrum and plotted against wavelength ( $\AA$ ).


Figure 2.7 Integrated spectra of the blue merger subsample obtained by the drift scanning technique. $F_{\lambda}$ is normalized to the mean value for the spectrum and plotted against wavelength $(\AA)$.


Figure 2.8 Integrated spectra of the blue merger subsample obtained by the drift scanning technique. $F_{\mathrm{N}}$ is normalized to the mean value for the spectrum and plotted against wavelength $(\AA)$.


Figure 2.9 Integrated spectra of the blue merger subsample obtained by the drift scanning technique. $F_{\lambda}$ is normalized to the mean value for the spectrum and plotted against wavelength $(\AA)$.


Figure 2.10 Comparison of our spectra (solid line) with previously published spectra. NGC 520 and NGC $5278 / 9$ are from LK95. NGC 3921 and NGC 4194 are taken from K92. $F_{\lambda}$ is normalized to the mean value for the spectrum and plotted against wavelength $(\mathcal{A})$. Our spectra are shifted upward by 0.3 flux units for clarity.

## Chapter 3

## Models and Fitting Procedure

We fit a series of two-component (two-burst) EPS models to each galaxy spectrum. to analyze the stellar content of the galaxies in the red merger and control samples. The solutions formally provide us with the progenitor type, burst age and strength. and corresponding uncertainties for each galaxy. In addition, a study of the input parameters of our models gives us an estimate of the uncertainty associated with each.

### 3.1. The Models

### 3.1.1. Evolutionary Population Synthesis

Evolutionary population synthesis is a method by which the evolution of a stellar population is modeled. The premise of EPS modeling is simple: choose a model for the star formation in a galaxy, and with information about the stellar physics at each evolutionary state, the evolution of a stellar population can be predicted. Stellar physics inputs include stellar evolutionary tracks for stars of various masses
and metallicities and the stellar spectrum that is observed at each evolutionary point, either based on actual observations of stars or stellar atmospheres models. A model of star formation must include an initial mass function (LMF) and a star formation rate as a function of time. In practice. this is difficult to do. The metallicity evolution of a population should be taken into account as the older stars enrich the IS.M that gives birth to younger stars. Line emission by ionized gas and dust obscuration affect observations. Few high metallicity stars are available to test their evolutionary tracks and stellar atmosphere models. or to make an empirical stellar library. time. Different EPS codes choose different means of dealing with these effects and may use different input elements in constructing synthetic spectra. A summary of the state of the art in constructing the elements of EPS models and the codes that assemble them and handle the problems described above can be found in Leitherer et al. (1996).

For this thesis. we make use of both the Bruzual \& Charlot (1998) GISSEL96 and Fioc \& Rocca-Volmerange (1997) PEGASE EPS model packages. We found the results from the GISSEL96 and PEGASE models generated with our adopted inputs (Section 3.1.2) to be virtually indistinguishable. so we present only the results from the PEG.ASE models here. unless otherwise noted.

### 3.1.2. Adopted Models

Both the GISSEL96 and PEGASE models allow some choice in the input elements. We chose to work with models of solar metallicity stars. since any star formation occurring in a merger will presumably occur in gas already enriched by prior star formation. Solar metallicity models were generated with the Padova (Bressan et al. 1993) stellar evolutionary tracks and the Jacoby et al. (1984) stellar library. We chose a Salpeter (1955) IMF, since this provides better fits to the photoionization
rates and colors of galaxy disks than the Scalo (1986) IMF (Kennicutt et al. 1994). Lower and upper mass limits were $0.1 \mathrm{M}_{\odot}$ and $120 \mathrm{M}_{\odot}$, respectively.

With the inputs adopted above, the synthetic model spectra are determined solely by the star formation history. We chose a two-component star formation history, $R(t)$, motivated by the merger hypothesis for the formation of elliptical galaxies, where

$$
R(t) \propto \begin{cases}e^{-t / \tau_{1}} & , \quad t<t_{1} \\ e^{-t / \tau_{2}} & , \quad t_{1}<t<t_{0}\end{cases}
$$

and $t_{1}$ is the time between the epoch of galaxy formation and the beginning of the interaction-induced star formation (i.e. the merger), $t_{2}$ is the time elapsed since the merger, $t_{0}$ is the present time $\left(t_{1}+t_{2}\right), \tau_{1}$ is the time constant of star formation in the progenitor population and is closely related to progenitor galaxy type, and $\tau_{2}$ is the time constant for the merger-induced star burst. A schematic illustration of this star formation history is shown in Figure 3.1. Star formation in the progenitor galaxies is truncated as the interaction-induced burst begins at $t_{1}$, but those stars continue to evolve passively until time $t_{2}$ has passed. Both progenitor galaxies are assumed to have the same time constant, $\tau_{1}$. We varied the time constant of the first burst, $\tau_{1}$, over the range 1-15 Gyr to simulate a range of progenitor types from elliptical to Sd galaxies. The time elapsed since the merger, $t_{2}$, was varied from $10^{7}$ to $1.6 \times 10^{9}$ years. This created a grid of EPS models to fit to the galaxy spectra. The time of the merger, $t_{1}$, was held fixed at 10 Gyr , while the burst timescale, $\tau_{2}$, remained constant at $10^{8}$ years, a value chosen since numerical simulations show that merger-induced star bursts are typically short in duration (Mihos \& Hernquist 1994b). Each spectrum was scaled to represent a burst of total mass $1 \mathrm{M}_{\odot}$. The ratio of the mass of the young burst to the total stellar mass, $f_{b}$, is calculated by the fitting program.

### 3.2. The Fitting Procedure

### 3.2.1. Description

Each pair of EPS template spectra were fitted to the galaxy spectrum using the fitting program described in Rix et al. (1995). A linear continuum spectrum with a mean value of zero was fit and removed from each spectrum along with the EPS templates to reduce problems caused by reddening or calibration error altering the continuum shape. This corrects slope errors without effecting the mean flux value of the spectrum, thereby minimizing changes to absolute equivalent widths. Tests on artificial galaxy spectra showed that this was the optimal compromise-with no continuum fit, reddening or calibration error alter the results, and a higher order fit removes too much of the continuum shape information.

For each input pair of mass-normalized template spectra, representing the progenitor and the "young" burst populations, respectively, the fitting program finds the ratio of the two which provides the best fit to the galaxy spectrum, from which $f_{b}$ is calculated, and a measure of the goodness of that fit, $\chi^{2}$, where

$$
\chi^{2}=\sum_{\lambda}\left(g_{\lambda}-m_{\lambda}\right)^{2},
$$

and $g_{\lambda}$ is the observed galaxy spectrum and $m_{\lambda}$ is the model. Even though $\chi^{2}$ is defined in the conventional way, Poisson errors are not the dominant source of uncertainty. Hence, we defined the value of $\Delta \chi^{2}$, within which the fit could be considered acceptable, through Monte-Carlo simulations. We added typical observational errors, both calibration errors and Poisson noise to a galaxy spectrum; twenty "distorted" spectra were generated with calibration errors in the form of a straight line, with slope (end-to-end) drawn randomly from a Gaussian of $\sigma=10 \%$. This is the pattern seen in the night-to-night comparisons of our spectra.

Twenty more spectra were generated, with the calibration errors represented by a sine wave with random phase and peak-to-peak amplitude drawn randomly from a Gaussian with $\sigma=10 \%$ to simulate the spectrophotometric differences between our sample and the K92 and LK95 galaxies. Poisson noise was added, assuming a signal-to-noise of 50 . Templates were then fit to the initial galaxy spectrum and the distorted spectra. The $\chi^{2}$ values for the distorted spectra were less than $2 \%$ greater than that of the initial spectrum in the mean with $1-\sigma$ scatter reaching $5 \%$. This indicates that observational errors can change $\chi^{2}$ by up to $5 \%$, and all template fits with values of $\chi^{2}$ within $5 \%$ of the minimum should be considered acceptable fits.

Fitting the grid of template spectra to any given galaxy spectrum results in a grid of quality of fit $\chi^{2}\left(\tau_{1}, t_{2}\right)$ and "burst fraction" $f_{b}\left(\tau_{1}, t_{2}\right)$. See Figures 4.1 and 4.2 for an example. We define the smallest value of $\chi^{2}$ on this grid to be $\chi_{\text {min }}^{2}$ with corresponding values of $\tau_{1}, t_{2}$, and $f_{b}$; this is the "best fit." To calculate uncertainties for these minimum values we fit a second order Taylor expansion to the surface around $\chi_{\text {min }}^{2}$, and found the points at which this paraboloid reaches the $\chi^{2}=\chi_{\text {min }}^{2}+\Delta \chi^{2}$ contour. This works well when the best fit is a true minimum and not the lowest value along the edge of the grid and when the Taylor expansion is an adequate description of the area around the minimum. When one of these conditions is not met, the calculation of uncertainties may fail. In these cases we derive uncertainties or limits from examination of the grid of fitting results, and note this in the table summarizing the results for each galaxy. We note that the function, $e^{-t / \tau_{1}}$, is discontinuous as $\tau_{1}$ goes to zero. For this reason, uncertainties in $\tau_{1}$ large enough to imply $\tau_{1}<0$ should be interpreted as one-sided uncertainties only, since they are an artifact of assuming the grid is continuous in both $\tau_{1}$ and $t_{2}$ for the purposes of calculating those uncertainties.

In addition to finding the best fitting solution and its uncertainty, we can set limits on the stellar populations based on all acceptable solutions. The mean age of the stars in any EPS model can be calculated by

$$
<t>=\frac{\int_{0}^{t_{0}} R(t)\left(t_{0}-t\right) d t}{\int_{0}^{t_{0}} R(t) d t}
$$

where $t_{0}=t_{1}+t_{2}$ is the total age of the galaxy at the current epoch. Upper and lower limits are calculated simply from the acceptable solutions with the highest and lowest values. We can also find the maximum mass of all stars younger than a given age, in both progenitor and induced burst. that is allowed by the acceptable solutions, as well as the minimum young stellar mass required by the solutions.

### 3.2.2. Emission Lines

The models we generated were made with stellar continua only: emission lines were not calculated and added to the model spectra. We used the following procedure to remove emission lines from the blue galaxy sample so wavelength regions important in determining stellar populations, for example the H 3 region. would not have to be excluded from the fit. First, we fit the grid of stellar models to each galaxy spectrum with the wavelength regions around the emission lines excluded from the fit. We then fit and subtracted a very high order ( $\sim 50$ ) function to the residual of the best-fitting solution, with the regions around the emission lines again excluded. This was saved as a temporary residual spectrum. This residual spectrum was cleaned of highly deviant points (the emission lines), and then subtracted from the saved residual spectrum, leaving a spectrum of only emission lines. The emission line spectrum was edited to remove any noise spikes that remained and subtracted from the original galaxy spectrum, leaving a galaxy spectrum free of emission lines. This procedure may introduce an error in the absorption line equivalent widths; however, since the entire spectrum is used in the fitting procedure, the
uncertainty introduced is small. Fitting results to a spectrum excluding emission line regions and to the entire emission line-cleaned spectrum are the same within the uncertainty limits described above.

The red merger sample, by selection, was relatively free of emission lines. Some of the red mergers did have weak $\mathrm{H} \alpha$ and [O II] $3727 \AA$ emission, however. Since these wavelength regions give less critical information about the stellar populations in the galaxy than other uncontaminated wavelength regions, we simply excluded the $\mathrm{H} \alpha$ and [O II] $3727 \AA$ regions from the subsequent fitting procedure.

### 3.2.3. Examples

To illustrate how the fitting process works, we have fit the grid of model spectra to four galaxy spectra, NGC 4194, IC 883, NGC 7727, and an artificial galaxy spectrum described in Section 3.2.4. Figure 3.2 shows the fitting results for the model grid. The burst age, $t_{2}$, is plotted logarithmically along the vertical axis, while progenitor type $\tau_{1}$ is plotted along the horizontal. Each point in the grid represents one possible star formation history and has an associated optimal burst mass fraction, $f_{b}$, and $\chi^{2}$ output by the fitting program. $\chi^{2}$ is contoured with solid lines, and $f_{b}$ with dashed lines. The best fit is marked with a cross. The first $\chi^{2}$ contour is the $5 \%$ contour, and all regions within it are acceptable solutions. Mass contours begin at $0.1 \%$ at young burst ages and increase toward older burst ages. For example, the fit for NGC 4194 has a minimum at $\tau_{1}=15$ and $\log t_{2}=8.6$. The area of acceptable fits lies between the $f_{b}=2 \%$ and $5 \%$ contours. NGC 4194's burst age is relatively well constrained with an uncertainty of about $0.1 \log \mathrm{yr}$, but its progenitor type is not, with $\tau_{1} \gtrsim 5 \mathrm{Gyr}$, ruling out only galaxy types earlier than Sb . The best fit and uncertainties derived from these data are given in Table 3.1 and mean age and young stellar mass limits based on
all acceptable solutions are shown in Table 3.2. The limits on young stellar mass includes contributions from both the progenitor and the interaction-induced star burst, and should not be confused with $f_{b}$ which is the burst mass alone. The best fitting models and residuals for the four galaxies are shown in Figures 3.3 and 3.4. The emission line subtracted galaxy spectrum is shown as a series of triangular points. The best fitting model is over plotted as a heavy line. Shown at smaller scale, it is often difficult to distinguish between the model and galaxy. We have therefore plotted the residual (galaxy minus model) as a dot-dashed line along the bottom of the graph. The individual components of the model are also plotted-the progenitor population as a dashed line, the burst population as a dotted line, and the continuum as a long dashed line. The model for NGC 4194 gives a reasonable fit, with the largest residual near the $\mathrm{H}_{\gamma}$ absorption line. The blue end of the spectrum is dominated by light from a young burst, with strong Balmer absorption while the light from the red end comes mostly from the progenitor population. still somewhat blue itself from recently formed stars in the progenitor spiral. Best fitting models for the other three galaxies are plotted in a similar fashion.

### 3.2.4. Tests

We tested this fitting method by constructing an artificial galaxy with known properties, and then fitting this artificial galaxy spectrum with the procedure outlined above. We constructed a galaxy with $\tau_{1}=2, \log t_{2}=8.8$, and $f_{b}=3 \%$. The young burst was reddened with $A_{V}=0.1 \mathrm{mag}$ and added to the old burst. The resulting spectrum was convolved with a Gaussian to simulate at $300 \mathrm{~km} \mathrm{~s}^{-1}$ velocity dispersion, multiplied by a $10 \%$ end-to-end calibration error, and finally Poisson noise representing $\mathrm{S} / \mathrm{N}=50$ was added. The resulting grid with $\chi^{2}$ and $f_{b}$ contours is shown in Figure 3.2 at the lower right. The best fit values are given
in Table 3.5. The recovered values were $\tau_{1}=2 \pm 7.7, \log t_{2}=8.9 \pm 0.0$, and $f_{b}=7.6 \pm 3.3 \%$. These are in good agreement with the input values, although the mass fraction found is slightly higher than the input values, even at the correct burst age and progenitor type, at $3.91 \%$ versus the $3 \%$ input.

A test of the fitting method and validity of the confidence limits based on observational constraints is to compare the fitting results from the same galaxy observed independently on separate nights. Such a comparison is presented in Tables 3.3 and 3.4 and Figures 3.5 and 3.6.

The results of the analysis of the two independent spectra of NGC 520 are in good agreement. The best fitting solutions are well within each other's acceptable limits, the solutions have similar relative contributions from young and old populations, and the contour plots showing the burst mass and quality of fit on the grid of model solutions are qualitatively as well as quantitatively very similar. This is also the case for NGC 4194. The agreement between the independent analyses of NGC 3921 is not as good but still acceptable. Solutions are the same to within their combined errors. The $\chi^{2}$ contour plots are still qualitatively similar, but the K92 spectrum analysis results in burst fraction contours which are moved down with respect to those resulting from the analysis of our spectrum. The best fitting solutions in Figure 3.6 show the best fitting solution for my spectrum has a larger contribution of light from young stars than the K92 spectrum solution. Finally, the comparison between NGC 5278/9 represents the worst case. The $\chi^{2}$ and burst fraction contour plots are qualitatively quite different, best fitting solutions are outside each other's acceptable limits, and the light fractions contributed in the solutions are markedly different, with the analysis of my spectrum resulting in a mix between young and old populations, while LK95 results in a spectrum
dominated by an old population.

Finally, we tested whether additional errors could be introduced in the comparison of the merger and control samples due to difference in the way the spectra were acquired. The red and blue ends of the control sample were acquired and reduced separately, and then spliced together (K92), while entire wavelength range of the merger sample was acquired with a single observation. The entire EPS fitting process was repeated for both samples using only the blue ( $\lambda<5150 \lambda$ ) ends of the spectra. The results from the shorter wavelength fits were consistent with those using the entire wavelength range.

### 3.3. Parameter Study of Systematic Effects

In the previous section, we derived $\chi^{2}$ limits within which a fit should be considered acceptable based on observational uncertainties, primarily calibration errors and signal-to-noise. There is also uncertainty associated with the input parameters we chose for the EPS models we use to fit the data. The choice of well constructed stellar library or stellar evolutionary tracks should make little difference to the analysis of stellar populations in a galaxy, and we varied our choice to make sure this was indeed the case. However, metallicity, IMF, and the star formation history may indeed change from galaxy to galaxy, and we wish to measure the changes of the stellar populations analysis by varying each of these parameters within reasonable physical limits. To perform both kinds of tests, we varied each parameter in turn and fit the resulting EPS model grids to the spectra of three representative galaxies from the merger sample, as well as the artificial galaxy spectrum described above. In each of these test only one parameter was varied at a time; the rest remained fixed at our adopted input parameters, described in

Section 3.1.2 above.

We chose a starburst galaxy, NGC 4194, an "E+A" type galaxy, IC 883, and a galaxy with little ongoing star formation, NGC 7727 , for this parameter study. The results of fitting the grid of our adopted models to these spectra, i.e. the $\gamma^{2}$ and burst mass contours, shown in Figure 3.2 and the best fitting solutions are shown in Figures 3.3 and 3.4.

### 3.3.1. Stellar Library

We fit each of our test galaxies using EPS models constructed with three different stellar libraries, our adopted Jacoby et al. (1984) stellar library, the Fioc \& Rocca-Volmerange (1997) standard library, and from the Bruzual \& Charlot (1998) models, the Kurucz (1995) stellar atmospheres library. Before fitting the Kurucz models, it was necessary to degrade our galaxy spectra approximately to the resolution of the Kurucz library models, 20 A. This was not necessary for the Jacoby and FRV libraries which had comparable or better resolution than our observed spectra, at $1.4 A, 10 A$, and $7.5 A$ respectively.

The results of this test are summarized in Tables 3.5 and 3.6 and fitting grids shown in Figures 3.2, 3.7. 3.17. The fitting results for each galaxy fit with the three different models agree to within the observationally defined uncertainty, although these uncertainties are large in several cases. This suggests that the choice of stellar library in making an EPS model adds little to the uncertainty in our results.

### 3.3.2. Stellar Evolution Tracks

Two sets of stellar evolution tracks are available to generate models within the PEGASE package, the Padova tracks which we have adopted, and the Geneva
tracks (Schaller et al. 1992, Charbonnel et al. 1996). The results of fitting our four test galaxies to models generated with these two sets of tracks are given in Tables 3.7 and 3.8 and Figures 3.2 and 3.8.

The choice of stellar evolution tracks makes little difference. The results are generally within the uncertainties defined by observation uncertainties.

### 3.3.3. Star Formation History

We varied the star formation history of the models in three different ways. We varied the decay constant of the interaction-induced star burst, $\tau_{2}$, by a factor of 2. This is consistent with the range of starburst duration found by Mihos and Hernquist (1994b). We also looked at the effect of increasing the age at which the merger occurs, $t 1$, to 12 Gyr. In addition, we allowed star formation in the progenitor population to continue unchanged during and after the merger, instead of truncating it at the merger. Finally, we allowed for a merger-induced burst of constant, continuing star formation, rather than a decaying burst. Results are in Tables 3.9 and 3.10.

As the burst time constant, $\tau_{2}$, increases, the length of time since the burst increases slightly. This is the expected result: the time between the last significant amount of star formation stays relatively constant. Mass limits on young stars remains the same within the expected errors. Full grid fits can be compared in Figures 3.9, 3.2, and 3.10.

Changing the age at which the merger occurs, $t_{1}$, has relatively little effect. The values found for burst time constant, $\tau_{2}$, age of merger-induced burst, $t_{2}$, and burst mass fraction and mass limits all remain the same. Again, this result is expected, since it is difficult to distinguish a 10 Gyr stellar population from a 12

Gyr one. The mean age of the stars in the mergers increase by 2 Gyr. suggesting the mean age of of the stars in the galaxies can be simply modified to reflect the chosen epoch of galaxy formation.

The results of allowing normal star formation to continue during and after the merger are more complicated. The progenitor galaxy type, $\tau_{1}$, decreases slightly, or moves to earlier type galaxies, but still within the errors. The mean age is nearly identical. The mass in young stars allowed by the models in the blue galaxies is increased by a factor of 2 . The $\chi^{2}$ surface is much more complicated however. These are presented in Figure 3.12. In addition to the pattern seen in the standard $\chi^{2}$ surfaces (e.g. Figure 3.7) the blue galaxies, NGC 4194 and IC 883 may also have a 1 Gyr old merger-induced burst. In this star formation scenario, the red galaxies, NGC $\pi T_{2} \bar{i}$ and the artificial galaxy, have spiral-type progenitors ( $\tau_{1} \gtrsim 3$ ) strongly excluded.

The results of fitting an interaction-induced burst of constant star formation. $\tau_{2}=\infty$, are also qualitatively different from our adopted models, as shown in Figure 3.13. For the blue galaxies, young bursts in late-type progenitors are preferred. Mass limits on young stars remain about the same, as do mean ages. Burst masses are the same, within the uncertainties, but burst age, $t_{2}$, decreases slightly.

### 3.3.4. Initial Mass Function

Several authors have claimed to find evidence for star formation in mergers with an IMF biased toward high mass stars than the local IMF, usually assumed to be a Scalo (1986) IMF (e.g. Bernlöhr 1992, Englebracht 1997). A Salpeter (1955) LMF is also more biased toward high mass star formation than the Scalo (1986) IMF and
provides a better fit to the integrated photoionization rates and colors of galaxy disks than the Scalo IMF (Kennicutt et al. 1994). In addition to the Salpeter and Scalo models, we looked at burst models with IMFs \#10 and \#11 from Rieke et al. (1993), both biased toward high mass star formation, and with the Scalo IMF serving as the IMF for the progenitor population. The results are summarized in Tables 3.11 and 3.12. The full grid fitting results are shown in Figures 3.2, 3.14, 3.15, and 3.16.

Using the Scalo IMF for both the burst and progenitor populations, the best fit values for burst age, $t_{2}$, and progenitor type $\tau_{1}$ are consistent with those found with the Salpeter models. The $\chi^{2}$ contours are qualitatively similar for both IMFs. In the two blue galaxies, NGC 4194 and IC 883. the burst mass increases by approximately a factor of two. This increase in burst mass is not seen in the red galaxies, NGC 7727 and the artificial galaxy. This is expected since at burst ages of $\sim 1$ Gyr, the high mass stars where the two IMFs differ have evolved through their stellar lifetimes. The mass limits derived with the Scalo models are about a factor of 0.75 times higher than those derived from the Salpeter models.

The fitting results from the Rieke IMF models are similar to those of the Salpeter IMF models. The contours are again qualitatively very similar and the best fits consistent. The mass limits from the Rieke IMF bursts are quite similar to those from Salpeter-derived mass limits.

### 3.3.5. Metallicity

Metallicity varies from galaxy to galaxy, and also among the stellar populations within an individual galaxy. It is therefore important to look at the effects of varying metallicity on the fitting results. The GISSEL96 (Bruzual \& Charlot 1998)

EPS models provide a series of populations that vary in metallicity and are based on the Kurucz (1995) model atmospheres. We showed in Section 3.3.1 that the fitting results from solar metallicity Kurucz atmospheres were consistent with those of standard empirical libraries, so changing the solar metallicity stellar library will result in little additional uncertainty. The accuracy of this test is limited by the accuracy of the atmospheres themselves, for which few observations of high metallicity stars are available for comparison.

We looked at the fitting results of four sets of models with varying metallicity, solar ( $Z=0.020$ ), sub-solar $(Z=0.008)$, super-solar ( $Z=0.050$ ), and a mixed metallicity set with a sub-solar progenitor and a super-solar burst. The results are shown in Figures 3.17, 3.18, 3.19, and 3.20 and summarized in Tables 3.13 and 3.14. Changing the metallicity of the progenitor population and/or the burst populations had little effect on the blue test galaxies. This is the expected result since the light from these galaxies is dominated by young stars with few metal lines. The red galaxies are affected, however. The $\chi^{2}$ contour plots are similar and $\tau_{1}$ and $t_{2}$ are consistent within the errors. The mass of the best fit burst population increases slightly but still within the errors. The striking result is seen in the mass limits. For the red test galaxies, as metallicity increases, the mass limits also increase. For an increase in Z of a factor of 2.5 , the mass in young stars also increases by a factor of 2.5. This is in the sense of the well-known age-metallicity degeneracy, where bluer early-type galaxies may be either more metal-poor or have more younger stars that a more red galaxy (e.g. Worthey 1994). The mixed metallicity models yield higher burst masses than solar models but less than a pure super-solar metallicity model.

### 3.3.6. Reddening

While the red merger subsample is unlikely to be significantly affected by reddening. the blue merger subsample, with on-going star formation. almost certainly will be. To test our fitting method in the presence of reddening. several more artificial galaxy spectra were constructed. These spectra all had unreddened S0/Sa type progenitors ( $\tau_{1}=3$ ) and a interaction-induced reddened burst consisting of $20 \%$ of the stellar mass of the galaxy. The spectra differed only in the amount of extinction the burst suffered, with $A_{V}$ ranging from 0.0 up through 10 mag. . .o other sources of noise or uncertainty were added to the spectra. These are shown in Figure 3.21. The presence of young stars is seen clearly up to $A_{1}=2 \mathrm{mag}$.

Each of these spectra was fit to the grid of models. The best fit for each galaxy is shown in Figure 3.21 and tabulated in Table 3.1.5. The best fit found for each spectrum is quite reasonable. The age of the burst is recovered in all cases. but the mass found decreases dramatically as the extinction increases. This appears to happen for two reasons. First. as the luminosity of the burst decreases. the mass found for it correspondingly decreases. and second. as the burst gets more reddened, a higher mass is found for the redder progenitor burst. The mass found decreases from $20 \%$ to $13 \%$ for $A_{v}$ of only 0.1 mag . $B y \cdot A_{V}=0.5 \mathrm{mag}$. the mass found decreases to about $5 \%$, and at 1 mag the mass is down by an order of magnitude to about $2 \%$.

The test indicates that reddening creates the largest source of uncertainty in the entire fitting method. With such large errors it is important to develop a strategy to deal with the presence of dust in some way. Such strategies and their results are discussed in Chapter 5.

### 3.3.7. Summary of Parameter Study

The main results of the parameter study are as follows.

- The choice of well-constructed stellar library or stellar evolution tracks for use in the EPS models does not significantly affect the fitting results.
- Varying the star formation history within our basic history makes little difference in the young stellar masses or mass limits found. Increasing or decreasing the burst duration, $\tau_{2}$. results in slightly older or younger burst ages. respectively. Increasing the galaxies* ages at the time of merger. $t_{1}$, has no affect on the burst age or mass found.
- Changing the IMF can affect the burst mass found in galaxies with light dominated by young stars. Scalo IMF models result in burst masses that are higher than those from Salpeter IMF models by almost a factor of two. The Salpeter and Rieke IMFs, both weighted toward high mass star formation. produce similar burst masses.
- Changing the metallicity can affect the burst mass found in galaxies that have spectra like those of early-type galaxies. We reproduce the well-known age-metallicity degeneracy. As metallicity of the models increases. the young stellar mass found also increases.
- Extinction and reddening caused by dust is the largest single source of uncertainty in the entire fitting procedure. The burst mass that is found depends sensitively on the amount of extinction that is present in the source.

Table 3.1. Example Galaxies-Best Fit

| Galaxy | $\chi_{\text {min }}^{2}$ | $\tau_{1}(\mathrm{Gyr})$ | $t_{2}(\log \mathrm{yr})$ | $f_{b}(\%)$ |
| :--- | ---: | :---: | :---: | :---: |
| NGC 4194 | 1611 | $1.5 \pm 10^{=}$ | $8.4 \pm 0.1^{*}$ | $3.2 \pm 2.5^{-}$ |
| IC 883 | 2208 | $11 \pm 7.6$ | $8.6 \pm 0.0$ | $7.5 \pm 0.8$ |
| NGC 7727 | 1423 | $1 \pm 13.3$ | $8.9 \pm 0.2$ | $1.8 \pm 3.0$ |
| Art. Gal. | 765 | $2 \pm 7.7$ | $8.9 \pm 0.0$ | $7.6 \pm 3.3$ |

*Uncertainties or limits derived by eye from contour plot.

Table 3.2. Example Galaxies-Limits

| Galaxy | $<$ age $>$ | Max \% |  | Min \% |  |
| :--- | :---: | :---: | :---: | :---: | :---: |
|  |  | $<1$ Gyr | $<0.5$ Gyr | $<1$ Gyr | $<0.5$ Gyr |
| NGC 4194 | $5.6_{-0.0}^{+1.8}$ | 9.53 | 6.10 | 4.59 | 3.99 |
| IC 883 | $5.5_{-0.0}^{+3.4}$ | 11.65 | 8.34 | 5.22 | 5.21 |
| NGC 7T27 | $9.6_{-3.2}^{+0.2}$ | 3.30 | 0.59 | 0.02 | 0.00 |
| Art. Gal. | $8.2_{-1.9}^{+0.9}$ | 9.20 | 1.06 | 3.91 | 0.38 |

Table shows the mean age of the stars in the galaxy, and the minimum and maximum amounts of young stars (less than 0.5 or 1 Gyr old) required by the EPS model fits.

Table 3.3. Comparison of Results from Independent Spectra-Best Fit

| Galaxy | $\chi_{\min }^{2}$ | $\tau_{1}(\mathrm{Gyr})$ | $t_{2}(\log \mathrm{yr})$ | $f_{b}(\%)$ |
| :--- | :---: | :---: | :---: | :---: |
| NGC 520 | 2443 | $6 \pm 2.5^{\dagger}$ | $7.7 \pm 0.7$ | $0.1 \pm 0.8$ |
| NGC 520 | 3882 | $8 \pm 8.3$ | $7.9 \pm 1.4$ | $0.3 \pm 2.6$ |
| NGC 3921 | 427.5 | $2 \pm 24.9$ | $8.9 \pm 0.2^{\dagger}$ | $1.5 .3 \pm 6.8$ |
| NGC 3921** | 2743 | $2 \pm 15^{\dagger}$ | $8.7 \pm 0.1$ | $6.6 \pm 4.9$ |
| NGC 4194 | 1611 | $1.5 \pm 10^{\dagger}$ | $8.4 \pm 0.1^{\dagger}$ | $3.2 \pm 2.5^{\dagger}$ |
| NGC 4194** | 3472 | $15 \pm 23.6$ | $8.2 \pm 0.3$ | $2.9 \pm 1.9$ |
| NGC 5278/9 | 3516 | $1 \pm 44.6$ | $8.9 \pm 0.1$ | $9.5 \pm 8.4$ |
| NGC 5278/9* | 4442 | $9 \pm 6.9$ | $7.9 \pm 0.7^{\dagger}$ | $<0.3^{\dagger}$ |

${ }^{\dagger}$ Uncertainties or limits derived by eye from contour plot.
*Spectrum from Liu \& Kennicutt (1995)
**Spectrum from Kennicutt (1992)

Table 3.4. Comparison of Results from Independent Spectra-Limits

| Galaxy | $<$ age $>$ | Max \% |  | Min \% |  |
| :--- | :---: | :---: | :---: | :---: | :---: |
|  |  | $<1$ Gyr | $<0.5 \mathrm{Gyr}$ | $<1 \mathrm{Gyr}$ | $<0.5$ Gyr |
| NGC 520 | $6.4_{-0.4}^{+1.8}$ | 5.56 | 2.63 | 1.61 | 1.25 |
| NGC 520 | $6.1_{-0.5}^{+2.1}$ | 7.16 | 3.48 | 2.29 | 1.46 |
| NGC 3921 | $7.6_{-4.5}^{+1.6}$ | 61.87 | 2.17 | 6.23 | 0.35 |
| NGC 3921** | $8.0_{-2.5}^{+0.9}$ | 11.84 | 8.59 | 5.26 | 4.60 |
| NGC 4194 | $5.6_{-0.0}^{+1.8}$ | 9.53 | 6.10 | 4.89 | 3.99 |
| NGC 4194** | $5.5_{-0.1}^{+3.4}$ | 10.80 | 7.39 | 3.18 | 2.96 |
| NGC 5278/9 | $8.9_{-7.3}^{+0.3}$ | 30.92 | 2.75 | 2.54 | 0.05 |
| NGC 5278/9 | $6.0_{-0.4}^{+3.2}$ | 7.20 | 3.52 | 1.79 | 1.49 |

*Spectrum from Liu \& Kennicutt (1995)
**Spectrum from Kennicutt (1992)

Table 3.5. Stellar Library Tests-Best Fit

| Galaxy | $\chi_{\min }^{2}$ | $\tau_{1}$ (Gyr) | $t_{2}(\log \mathrm{yr})$ | $f_{b}(\%)$ |
| :--- | :---: | :---: | :---: | :---: |
|  | Jacoby et al. Stellar Library |  |  |  |
| NGC 4194 | 1611 | $15 \pm 10^{*}$ | $8.4 \pm 0.1^{*}$ | $3.2 \pm 2.5^{*}$ |
| IC 883 | 2208 | $11 \pm 7.6$ | $8.6 \pm 0.1^{*}$ | $7.5 \pm 0.8$ |
| NGC 7727 | 1423 | $1 \pm 13.3$ | $8.9 \pm 0.2$ | $1.8 \pm 3.0$ |
| Art. Gal. | 765 | $2 \pm 7.7$ | $8.9 \pm 0.1^{*}$ | $7.6 \pm 3.3$ |
|  | Kurucz Model Atmospheres |  |  |  |
| NGC 4194 | 1410 | $14 \pm 7.1$ | $8.4 \pm 0.0$ | $4.2 \pm 0.7$ |
| IC 883 | 948 | $15 \pm 0.1$ | $8.5 \pm 0.0$ | $5.8 \pm 1.0^{*}$ |
| NGC 7727 | 1819 | $1 \pm 15^{*}$ | $>9.0^{*}$ | $9.7 \pm 8.4$ |
| Art. Gal. | 1.34 .3 | $1 \pm 9.3$ | $8.9 \pm 0.1^{*}$ | $7.6 \pm 3.1$ |

Fioc \& Rocca-Volmerange Standard Library

| NGC 4194 | 2150 | $15 \pm 6.4$ | $8.3 \pm 0.1$ | $2.9 \pm 1.9$ |
| :--- | :---: | :---: | :---: | :---: |
| IC 883 | 3150 | $3 \pm 4.1$ | $8.5 \pm 0.0$ | $4.8 \pm 1.8$ |
| NGC 7727 | 2326 | $1 \pm 2.6$ | $9.1 \pm 0.2$ | $5.4 \pm 7.0$ |
| Art. Gal. | 1775 | $12 \pm 8.6$ | $8.4 \pm 0.4$ | $0.0 \pm 24.9$ |

*Uncertainties or limits derived by eye from contour plot.

Table 3.6. Stellar Library Tests-Limits

| Galaxy | < age > | Max \% |  | Min \% |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | <1 Gyr | $<0.5 \mathrm{Gyr}$ | <1 Gyr | $<0.5 \mathrm{Gyr}$ |
| Jacoby et al. Stellar Library |  |  |  |  |  |
| NG:C 4194 | $5.6{ }_{-0.0}^{+1.8}$ | 9.53 | 6.10 | 4.89 | 3.99 |
| LC 883 | $5.5{ }_{-0.0}^{+3.4}$ | 11.65 | 8.34 | 5.22 | 5.21 |
| NGC 7727 | 9.6 .3 -3.2 | 3.30 | 0.59 | 0.02 | 0.00 |
| Art. Gal. | $8.2{ }_{-1.9}^{+0.9}$ | 9.20 | 1.06 | 3.91 | 0.38 |
| Kurucz Model Atmospheres |  |  |  |  |  |
| NGC 41.94 | 5.6 | 9.37 | 5.90 | 6.29 | 4.55 |
| IC 883 | $5.5{ }_{-0.0}^{+0.8}$ | 10.44 | 7.05 | 8.18 | 6.21 |
| NGC 7727 | $9.4{ }_{-3.2}^{+0.2}$ | 4.82 | 0.66 | 0.05 | 0.00 |
| Art. Gal. | $9.1{ }_{-3.3}^{+0.0}$ | 10.34 | 1.16 | 4.23 | 0.41 |
| Fioc \& Rocca-Volmerange Standard Library |  |  |  |  |  |
| NGC 4194 | $5.6{ }_{-0.0}^{+3.4}$ | 9.33 | 5.85 | 2.75 | 2.75 |
| IC 883 | $7.3{ }_{-1.8}^{+1.6}$ | 10.45 | 7.06 | 3.97 | 3.96 |
| NGC 7727 | $9.8{ }_{-3.4}^{+0.0}$ | 2.59 | 0.58 | 0.02 | 0.00 |
| Art. Gal. | $5.9{ }_{-0.1}^{+3.4}$ | 8.62 | 2.27 | 2.45 | 0.33 |

Table 3.7. Stellar Evolution Tracks Test-Best Fit

| Galaxy | $\chi_{\text {min }}^{2}$ | $\tau_{1}(\mathrm{Gyr})$ | $t_{2}(\log \mathrm{yr})$ | $f_{b}(\%)$ |
| :---: | :---: | :---: | :---: | :---: |
| Padova Tracks |  |  |  |  |
| NGC 4194 | 1611 | $1.5 \pm 10^{*}$ | $8.4 \pm 0.1^{*}$ | $3.2 \pm 2.5^{*}$ |
| IC 883 | 2208 | $11 \pm 7.6$ | $8.6 \pm 0.1^{*}$ | $7.5 \pm 0.8$ |
| NGC 7727 | 1423 | $1 \pm 13.3$ | $8.9 \pm 0.2$ | $1.8 \pm 3.0$ |
| Art. Gal. | 765 | $2 \pm 7.7$ | $8.9 \pm 0.1^{*}$ | $7.6 \pm 3.3$ |
| Geneva Tracks |  |  |  |  |
| NGC 4194 | 1648 | $15 \pm 4.1$ | $8.5 \pm 0.1$ | $4.9 \pm 1.3$ |
| IC 883 | 2235 | $15 \pm 15.7$ | $8.6 \pm 0.1$ | $7.6 \pm 2.5{ }^{*}$ |
| NGC 7727 | 1475 | $1 \pm 11.7$ | $9.0 \pm 0.1$ | $3.4 \pm 1.6$ |
| Art. Gal. | 944 | $2 \pm 0.6$ | $8.9 \pm 0.1 *$ | $7.4 \pm 3.1$ |

*Uncertainties or limits derived by eye from contour plot.

Table 3.8. Stellar Evolution Tracks Test-Limits

| Galaxy | $<$ age $>$ |  | Max \% |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: |
|  |  | $<1$ Gyr | $<0.5$ Gyr | $<1$ Gyr | $<0.5$ Gyr |
| Padova Tracks |  |  |  |  |  |
| NGC 4194 | $5.6_{-0.0}^{+1.8}$ | 9.53 | 6.10 | 4.89 | 3.99 |
| IC 883 | $5.5_{-0.0}^{+3.4}$ | 11.65 | 8.34 | 5.22 | 5.21 |
| NGC 7727 | $9.6_{-3.2}^{+0.1}$ | 3.30 | 0.59 | 0.02 | 0.00 |
| Art. Gal. | $8.2_{-1.9}^{+0.9}$ | 9.20 | 1.06 | 3.91 | 0.38 |
|  |  | Geneva Tracks |  |  |  |
| NGC 4194 | $5.6_{-0.0}^{+1.3}$ | 9.59 | 6.16 | 6.11 | 4.53 |
| IC 883 | $5.5_{-0.0}^{+2.4}$ | 11.61 | 8.30 | 6.47 | 6.28 |
| NGC 7727 | $9.7_{-3.2}^{+0.0}$ | 3.43 | 0.39 | 0.03 | 0.00 |
| Art. Gal. | $8.3_{-2.0}^{+0.9}$ | 15.38 | 0.41 | 7.12 | 0.09 |

Table 3.9. Tests on $\operatorname{SFR}(\mathrm{t})$-Best Fit

| Galaxy | $\chi_{\text {min }}^{2}$ | $\tau_{1}(\mathrm{Gyr})$ | $t_{2}(\log \mathrm{yr})$ | $f_{b}(\%)$ |
| :---: | :---: | :---: | :---: | :---: |
| $t_{1}=10 \mathrm{Gyr}, \tau_{2}=5 \times 10^{7} \mathrm{yr}$ |  |  |  |  |
| NGC 4194 | 1596 | $11 \pm 7.4$ | $8.3 \pm 0.1$ | $2.8 \pm 0.7$ |
| IC 883 | 2198 | $15 \pm 3.2$ | $8.4 \pm 0.1$ | $4.2 \pm 7.0$ |
| NGC 7727 | 1426 | $1 \pm 5.0$ | $>8.7^{*}$ | $4.0 \pm 6.5$ |
| Art. Gal. | 721 | $2 \pm 0.2$ | $8.8 \pm 0.1$ | $5.3 \pm 2.1$ |
| $t_{1}=10 \mathrm{Gyr}, \tau_{2}=1 \times 10^{8} \mathrm{yr}$ |  |  |  |  |
| NGC 4194 | 1611 | $15 \pm 10^{*}$ | $8.4 \pm 0.1^{*}$ | $3.2 \pm 2.5^{*}$ |
| IC 883 | 2208 | $11 \pm 7.6$ | $8.6 \pm 0.0$ | $7.5 \pm 0.8$ |
| NGC 7727 | 1423 | $1 \pm 13.3$ | $8.9 \pm 0.2$ | $1.8 \pm 3.0$ |
| Art. Gal. | 765 | $2 \pm 7.7$ | $8.9 \pm 0.0$ | $7.6 \pm 3.3$ |
| $t_{1}=10 \mathrm{Gyr}, \tau_{2}=2 \times 10^{8} \mathrm{yr}$ |  |  |  |  |
| NGC 4194 | 1636 | $15 \pm 7.3$ | $8.6 \pm 0.1$ | $5.6 \pm 4.0$ |
| IC 883 | 2216 | $14 \pm 22.2$ | $8.8 \pm 0.1$ | $15.8 \pm 10.9$ |
| NGC 7727 | 1417 | $1 \pm 3.4$ | $9.1 \pm 0.1$ | $4.1 \pm 4.6$ |
| Art. Gal. | 819 | $11 \pm 4^{*}$ | $8.4 \pm 0.1 *$ | > 0.1 * |
| $t_{1}=12 \mathrm{Gyr}, \tau_{2}=1 \times 10^{8}$ |  |  |  |  |
| NGC 4194 | 1634 | $11 \pm 2.3$ | $8.5 \pm 0.1$ | $4.7 \pm 2.0^{*}$ |
| IC 883 | 2209 | $14 \pm 15.8$ | $8.6 \pm 0.1^{*}$ | $7.7 \pm 2.5^{*}$ |
| NGC 7727 | 1408 | $1 \pm 7.7$ | $>8.7^{*}$ | $3.2 \pm 6.8$ |
| Art. Gal. | 773 | $2 \pm 12.3$ | $8.9 \pm 0.1$ | $6.9 \pm 1.3$ |
| $t_{1}=10 \mathrm{Gyr}$ (continuing SF), $\tau_{2}=1 \times 10^{8}$ |  |  |  |  |
| NGC 4194 | 1625 | $15 \pm 9.2$ | $8.8 \pm 0.1^{*}$ | $10.3 \pm 9.2$ |
| IC 883 | 2231 | $10 \pm 2.2$ | >8.7** | $17.9 \pm 7.8$ |
| NGC 7727 | 1423 | $1 \pm 0.9$ | $8.9 \pm 0.2$ | $1.8 \pm 1.3$ |
| Art. Gal. | 769 | $1 \pm 0.5^{*}$ | $8.9 \pm 0.1^{*}$ | $7.2 \pm 4.0^{*}$ |
| $t_{1}=10 \mathrm{Gyr}, \tau_{2}=\infty$ |  |  |  |  |
| NGC 4194 | 1773 | $15 \pm 2.7$ | $7.0 \pm 0.7$ | $<1.5^{*}$ |
| IC 883 | 2693 | $15 \pm 3.5$ | $7.2 \pm 0.1$ | $<0.5^{*}$ |
| NGC 7727 | 1440 | $3 \pm 3.4$ | $8.5 \pm 0.5$ | $<0.5^{*}$ |
| Art. Gal. | 819 | $11 \pm 4.0^{*}$ | $8.4 \pm 0.1^{*}$ | $<0.1^{*}$ |

*Uncertainties or limits derived by eye from contour plot.

Table 3.10. Tests on $\operatorname{SFR}(\mathrm{t})$-Limits

| Galaxy | < age > | Max \% |  | Min \% |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | <1 Gyr | $<0.5 \mathrm{Gyr}$ | <1 Gyr | $<0.5 \mathrm{Gyr}$ |
| $t_{1}=10 \mathrm{Gyr}, \tau_{2}=5 \times 10^{7} \mathrm{yr}$ |  |  |  |  |  |
| NGC 4194 | $5 . i_{-0.1}^{+1.6}$ | 8.48 | 4.95 | 4.56 | 3.33 |
| IC S83 | $5.6_{-0.0}^{+3.4}$ | 10.75 | 7.37 | 4.38 | 4.38 |
| NGC 7727 | $9.6{ }_{-3.2}^{+0.0}$ | 4.00 | 0.75 | 0.00 | 0.00 |
| Art. Gal. | $8.3_{-1.7}^{+0.9}$ | 6.79 | 2.77 | 2.95 | 0.38 |
| $t_{1}=10 \mathrm{Gyr}, \tau_{2}=1 \times 10^{8} \mathrm{yr}$ |  |  |  |  |  |
| NGC 4194 | $5.6{ }_{-0.0}^{+1.8}$ | 9.53 | 6.10 | 4.89 | 3.99 |
| IC 883 | $5.5{ }_{-0.0}^{\text {a }}$ + ${ }^{\text {a }}$ | 11.65 | 8.34 | 5.22 | 5.21 |
| NGC 7727 | $9.6{ }_{-3.2}^{+0.1}$ | 3.30 | 0.59 | 0.02 | 0.00 |
| Art. Gal. | $8.2{ }_{-1.9}^{+0.9}$ | 9.20 | 1.06 | 3.91 | 0.38 |
| $t_{1}=10 \mathrm{Gyr}, \tau_{2}=2 \times 10^{8} \mathrm{yr}$ |  |  |  |  |  |
| NGC 4194 | $5.6{ }_{-0.1}^{+3.4}$ | 11.73 | 8.47 | 5.50 | 5.04 |
| IC 883 | $5.3{ }_{-0.9}^{+3.4}$ | 35.98 | 9.03 | 10.62 | 5.35 |
| NGC 7727 | $9.9{ }_{-3.4}^{+0.0}$ | 2.01 | 0.43 | 0.31 | 0.00 |
| Art. Gal. | $6.0_{-0.2}^{+0.3}$ | 5.40 | 1.78 | 3.94 | 1.20 |
| $t_{1}=12 \mathrm{Gyr}, \tau_{2}=1 \times 10^{8}$ |  |  |  |  |  |
| NGC 4194 | $7.6{ }_{-0.0}^{+1.8}$ | 9.61 | 6.18 | 4.40 | 3.71 |
| IC 883 | $7.50{ }_{-0.0}^{+3.5}$ | 11.78 | 8.48 | 4.58 | 4.57 |
| NGC 7727 | $11 . i_{-3.4}^{+0.0}$ | 3.23 | 0.70 | 0.0:3 | 0.00 |
| Art. Gal. | $10.3_{-2.5}^{+0.9}$ | 10.16 | 1.07 | 4.56 | 0.35 |
| $t_{1}=10 \mathrm{Gyr}$ (continuing SF), $\tau_{2}=1 \times 10^{8}$ |  |  |  |  |  |
| NGC 4194 | $5.7_{-0.1}^{+1.8}$ | 16.57 | 13.61 | 5.63 | 4.37 |
| IC 883 | $5.50{ }_{-0.3}^{+3.4}$ | 21.59 | 18.74 | 5.22 | 5.21 |
| NGC 7727 | $9.6{ }_{-1.2}^{+0.2}$ | 10.36 | 10.36 | 0.33 | 0.13 |
| Art. Gal. | $9.2 \pm 0.0$ | 7.19 | 7.19 | 7.19 | 7.19 |
| $t_{1}=10 \mathrm{Gyr}, \tau_{2}=\infty$ |  |  |  |  |  |
| NGC 4194 | $5.6_{-0.0}^{+0.1}$ | 8.20 | 4.58 | 6.74 | 3.36 |
| IC S83 | $5.6{ }_{-0.0}^{+0.1}$ | 7.27 | 3.60 | 6.57 | 3.18 |
| NGC 7727 | $7.7_{-1.3}^{+0.9}$ | 1.90 | 0.45 | 0.12 | 0.00 |
| Art. Gal. | $6.0_{-0.2}^{+0.3}$ | 5.40 | 1.78 | 3.94 | 1.20 |

Table 3.11. IMF Tests-Best Fit

| Galaxy | $\chi_{\text {min }}^{2}$ | $\tau_{1}(\mathrm{Gyr})$ | $t_{2}(\log \mathrm{yr})$ | $f_{b}(\%)$ |
| :---: | :---: | :---: | :---: | :---: |
| Salpeter IMF |  |  |  |  |
| NGC 4194 | 1611 | $15 \pm 10^{*}$ | $8.4 \pm 0.1^{*}$ | $3.2 \pm 2.5^{*}$ |
| IC 883 | 2208 | $11 \pm 7.6$ | $8.6 \pm 0.1^{*}$ | $7.5 \pm 0.8$ |
| NGC 7727 | 1423 | $1 \pm 13.3$ | $8.9 \pm 0.2$ | $1.8 \pm 3.0$ |
| Art. Gal. | 765 | $2 \pm 7.7$ | $8.9 \pm 0.1^{*}$ | $7.6 \pm 3.3$ |
| Scalo IMF |  |  |  |  |
| NGC 4194 | 1618 | $10 \pm 7.1$ | $8.4 \pm 0.1$ | $8.4 \pm 1.3$ |
| IC 883 | 2201 | $14 \pm 15^{*}$ | $8.5 \pm 0.2$ | $11.1 \pm 6.7$ |
| NGC 7727 | 1429 | $1 \pm 6.5$ | $8.8 \pm 0.2$ | $1.8 \pm 1.7$ |
| Art. Gal. | 763 | $2 \pm 14.9$ | $8.8 \pm 0.1$ | $6.7 \pm 5.0^{*}$ |
| Scalo IMF Progenitor, Rieke IMF (10) Burst |  |  |  |  |
| NGC 4194 | 1597 | $15 \pm 9.6$ | $8.4 \pm 0.1$ | $2.5 \pm 0.4$ |
| IC 883 | 2217 | $8 \pm 12.7$ | $8.6 \pm 0.2^{*}$ | $5.2 \pm 2.5^{*}$ |
| NGC 7727 | 1420 | $<4^{*}$ | $>8.5^{*}$ | $7.7 \pm 8.5$ |
| Art. Gal. | 741 | $2 \pm 8.3$ | $8.9 \pm 0.1$ | $7.4 \pm 4.0$ |
| Scalo IMF Progenitor, Rieke IMF (11) Burst |  |  |  |  |
| NGC 4194 | 1604 | $15 \pm 12.7$ | $8.5 \pm 0.1$ | $4.5 \pm 2.0^{*}$ |
| IC 883 | 2214 | $15 \pm 8.7$ | $8.6 \pm 0.1$ | $8.0 \pm 4.7$ |
| NGC 7727 | 1420 | $1 \pm 2.0$ | $>8.6{ }^{*}$ | $12.4 \pm 13.0$ |
| Art. Gal. | 757 | $2 \pm 10.0$ | $8.9 \pm 0.1^{*}$ | $11.8 \pm 7.0^{*}$ |

*Uncertainties or limits derived by eye from contour plot.

Table 3.12. IMF Tests-Limits

| Galaxy | < age > | Max \% |  | Min \% |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $<1$ Gyr | $<0.5 \mathrm{Gyr}$ | <1 Gyr | $<0.5 \mathrm{Gyr}$ |
| Salpeter IMF |  |  |  |  |  |
| NGC 4194 | $5.6_{-0.0}^{+1.8}$ | 9.53 | 6.10 | 4.89 | 3.99 |
| IC 883 | $5.5_{-0.0}^{+3.4}$ | 11.65 | 8.34 | 5.22 | 5.21 |
| NGC 7727 | $9.6{ }_{-3.2}^{+0.1}$ | 3.30 | 0.59 | 0.02 | 0.00 |
| Art. Gal. | $8.2_{-1.9}^{+0.9}$ | 9.20 | 1.06 | 3.91 | 0.38 |
| Scalo IMF |  |  |  |  |  |
| NGC 4194 | $5.3{ }_{-0.0}^{+2.4}$ | 13.49 | 10.18 | 7.33 | 7.13 |
| IC 883 | $5.2{ }_{-0.1}^{+3.3}$ | 18.05 | 14.98 | 8.25 | 8.25 |
| NGC 7727 | $9.5{ }_{-2.5}^{+0.2}$ | 4.67 | 1.16 | 0.03 | 0.00 |
| Art. Gal. | $8.2{ }_{-2.0}^{+0.9}$ | 12.87 | 1.89 | 6.25 | 0.59 |
| Scalo IMF Progenitor, Rieke IMF (10) Burst |  |  |  |  |  |
| NGC 4194 | $5 . i_{-0.0}^{+1.8}$ | 8.17 | 4.69 | 3.85 | 2.87 |
| IC 883 | $6.1_{-0.5}^{+3.0}$ | 9.47 | 6.07 | 3.77 | 3.66 |
| NGC 7727 | $9.6{ }_{-2.8}^{+0.1}$ | 3.45 | 0.66 | 0.03 | 0.00 |
| Art. Gal. | $8.3{ }_{-1.9}^{+0.9}$ | 8.91 | 0.92 | 3.83 | 0.37 |
| Scalo [MF Progenitor, Rieke IMF (11) Burst |  |  |  |  |  |
| NGC 4194 | $5.6{ }_{-0.0}^{+1.3}$ | 9.17 | 5.72 | 5.61 | 4.42 |
| IC 883 | $5.5{ }_{-0.3}^{+3.1}$ | 17.67 | 14.63 | 6.56 | 6.37 |
| NGC 7727 | $9.1{ }_{-2.8}^{+0.4}$ | 5.73 | 0.72 | 0.05 | 0.00 |
| Art. Gal. | $7.9_{-2.0}^{+0.9}$ | 13.63 | 0.67 | 11.04 | 0.59 |

Table 3.13. Metallicity Tests-Best Fit

| Galaxy | $\chi_{\text {min }}^{2}$ | $\tau_{1}(\mathrm{Gyr})$ | $t_{2}(\log \mathrm{yr})$ | $f_{b}(\%)$ |
| :---: | :---: | :---: | :---: | :---: |
| Solar Metallicity ( $\mathrm{Z}=0.02$ ), Kurucz Atmospheres |  |  |  |  |
| NGC 4194 | 1410 | $14 \pm 7.1$ | $8.4 \pm 0.1^{*}$ | $4.2 \pm 0.7$ |
| IC 883 | 948 | $15 \pm 0.1$ | $8.5 \pm 0.1^{*}$ | $5.8 \pm 1.0^{*}$ |
| NGC 7727 | 1819 | $1 \pm 15^{\circ}$ | $>9.0^{*}$ | $9.7 \pm 8.4$ |
| Art. Gal. | 1343 | $1 \pm 9.3$ | $8.9 \pm 0.1^{*}$ | $7.6 \pm 3.1$ |
| Sub-Solar Metallicity ( $Z=0.008$ ) |  |  |  |  |
| NGC 4194 | 1253 | $15 \pm 7.0$ | $8.4 \pm 0.1$ | $3.9 \pm 0.9$ |
| IC S83 | 881 | $14 \pm 9^{*}$ | $8.6 \pm 0.1$ | $7.7 \pm 0.5$ |
| NGC 7727 | 19.57 | $1 \pm 5.9$ | $9.2 \pm 0.5$ | $7.2 \pm 4.8$ |
| Art. Gal. | 1.578 | $1 \pm 9.0$ | $9.0 \pm 0.1$ | $8.6 \pm 1.3$ |
| Super-Solar Metallicity ( $\mathrm{Z}=0.0 .5$ ) |  |  |  |  |
| NGC 4194 | 17.51 | $1.5 \pm 7.9$ | $8.4 \pm 0.1^{*}$ | $4.5 \pm 0.8$ |
| IC 883 | 1232 | $1.5 \pm 7.0^{*}$ | $8.5 \pm 0.1^{*}$ | $6.7 \pm 2.0^{*}$ |
| NGC 720 | 2179 | $7 \pm 8.5$ | $8.6 \pm 0.2$ | $<10.0{ }^{*}$ |
| Art. Gal. | 17.53 | $14 \pm 12.4$ | $8.8 \pm 0.2=$ | $8.3 \pm 5.3$ |
| Sub-Solar Progenitor, Super-Solar Burst |  |  |  |  |
| NGC 4194 | 1339 | $1.5 \pm 7^{*}$ | $8.3 \pm 0.2^{*}$ | $2.6 \pm 1.4^{*}$ |
| IC 883 | 937 | $15 \pm 7^{=}$ | $8.5 \pm 0.1^{*}$ | $6.4 \pm 2.0^{*}$ |
| NGC 7727 | 1947 | $9 \pm 8.3$ | > 8.9* | $9.4 \pm 9.7$ |
| Art. Gai. | 1683 | $1 \pm 5.4$ | $8.8 \pm 0.0$ | $7.3 \pm 2.2$ |

- Uncertainties or limits derived by eye from contour plot.

Table 3.14. Metallicity Tests-Limits

| Galaxy | < age > | Max \% |  | Min \% |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | <l Gyr | $<0.5 \mathrm{Gyr}$ | $<1 \mathrm{Gyr}$ | $<0.5 \mathrm{Gyr}$ |
| Solar Metallicity ( $\mathrm{Z}=0.02$ ), Kurucz Atmospheres |  |  |  |  |  |
| NGC 4194 | $5.6{ }_{-0.0}^{+1.0}$ | 9.37 | 5.90 | 6.29 | 4.55 |
| IC 883 | $5.5{ }_{-0.0}^{+0.8}$ | 10.44 | 7.05 | 8.18 | 6.21 |
| NGC 7727 | $9.4{ }_{-3.2}^{+0.2}$ | 4.82 | 0.66 | 0.05 | 0.00 |
| Art. Gal. | $9.1{ }_{-3.3}^{+0.0}$ | 10.34 | 1.16 | 4.23 | 0.41 |
| Sub-Solar Metallicity ( $\mathrm{Z}=0.008$ ) |  |  |  |  |  |
| NGC 4194 | 5.6 .0 .0 | 10.18 | 6.77 | 6.23 | 4.18 |
| IC 883 | $5.5{ }_{-0.0}^{+1.7}$ | 11.72 | 8.41 | 8.22 | 7.58 |
| NGC 727 | $9.9 .{ }_{-3.3}^{+0.0}$ | 2.03 | 0.24 | 0.00 | 0.00 |
| Art. Gal. | $9.2{ }_{-2.3}^{+0.0}$ | 9.20 | 0.06 | 1.41 | 0.01 |
| Super-Solar Metallicity ( $\mathrm{Z}=0.05$ ) |  |  |  |  |  |
| NGC 4194 | $5.6{ }_{-0.0}^{+0.8}$ | 9.63 | 6.17 | 6.95 | 4.93 |
| IC 883 | $5.5{ }_{-0.0}^{+0.8}$ | 11.29 | 7.92 | 8.66 | 6.70 |
| NGC 7727 | $6.5_{-0.6}^{+2.5}$ | 11.61 | 1.34 | 2.00 | 0.07 |
| Art. Gal. | $5.7{ }_{-0.0}^{+1.8}$ | 10.69 | 4.25 | 5.58 | 1.93 |
| Sub-Solar Progenitor, Super-Solar Burst |  |  |  |  |  |
| NGC 4194 | $5.6{ }_{-0.0}^{+0.7}$ | 9.22 | 5.74 | 7.05 | 3.53 |
| IC 883 | $5.5 .{ }_{-0.0}^{+0.6}$ | 10.96 | 7.58 | 9.51 | 7.28 |
| NGC 7727 | $6.4{ }_{-0.1}^{+3.1}$ | 7.76 | 0.66 | 0.00 | 0.00 |
| Art. Gal. | $9.0{ }_{-3.4}^{+0.0}$ | 17.08 | 2.03 | 7.04 | 0.75 |

Table 3.15. Reddening Test-Results

| $A_{V}$ | $\tau_{1}$ (Gyr) |  |  | $\log t_{2}(\log \mathrm{yr})$ |  |  | $f_{b}(\%)$ |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Min | Best | Max | Min | Best | Max | Min | Best | Max |
| 0.0 | 3 | 3 | 3 | 8.0 | 8.0 | 8.0 | 19.9 | 19.9 | 19.9 |
| 0.1 | 5 | 5 | 6 | 8.0 | 8.0 | 8.0 | 13.2 | 13.2 | 13.9 |
| 0.2 | 5 | 6 | 8 | 8.0 | 8.0 | 8.0 | 9.0 | 9.5 | 10.2 |
| 0.5 | 5 | 6 | 9 | 8.0 | 8.0 | 8.0 | 4.3 | 4.5 | 4.9 |
| 1.0 | 2 | 4 | 1.5 | 7.5 | 8.0 | 8.1 | 0.7 | 1.9 | 2.2 |
| 2.0 | 1 | 4 | 5 | 7.0 | 7.1 | 8.1 | 0.1 | 0.1 | 0.8 |
| 5.0 | 2 | 2 | 2 | 7.8 | 7.8 | 7.8 | 0.1 | 0.1 | 0.1 |
| 10. | 3 | 3 | 3 | 8.1 | 8.1 | 8.1 | 0.0 | 0.0 | 0.0 |



Figure 3.1 Schematic illustration of $\mathrm{R}(t)$. The burst time constant. $\tau_{2}$, is fixed at $10^{8} \mathrm{yr}$, and galaxy age at the time of the merger, $t_{1}$, at 10 Gyr . $\tau_{1}$, representing the progenitor galaxy type, and $t_{2}$, the time elapsed since the merger. are allowed to vary.


Figure 3.2 Results of fitting our adopted EPS models to four test galaxies. Burst age, $t_{2}$, is plotted against progenitor type, $\tau_{1} \cdot \chi^{2}$ is contoured with solid lines and young burst mass fraction, $f_{b}$, with dashed lines. The location of $\chi_{\text {min }}^{2}$ is marked with a cross. $\chi^{2}$ is contoured at $(1.05,1.1,1.2,1.5,2,5,10,20,50) \chi_{\text {min }}^{2} . f_{b}$ is contoured at $(0.1,0.2,0.5,1,2,5,10,20,50,100)$ percent total stellar mass fraction increasing in all cases from bottom to top of graph.


Figure 3.3 Best fit and residuals for NGC 4194 and IC 883 using our adopted models. The emission line-cleaned galaxy spectrum is plotted as a series of points, the best fit model is plotted as a solid line, the progenitor populations as a dashed line, the burst population as a dotted line, the continuum contribution as a long-dashed line, and the residual is plotted as a dot-dashed line.


Figure 3.4 Best fit and residuals for NGC 7727 and the artificial galaxy spectrum using our adopted models. Galaxy, model, and residuals are as plotted in Figure 3.3.


Figure 3.5 Fitting results for galaxies with independently acquired spectra. Symbols and contours are as in Figure 3.2. The comparison is good for NGC 520 and NGC 4194, adequate for NGC 3921, and relatively poor for NGC 5278/9.


Figure 3.6 Best fit and residuals for galaxies with independently acquired spectra. Galaxy, model, and residual are plotted as in Figure 3.3.


Figure 3.7 Results for test galaxies fit with models made with the FRV standard stellar library. All other parameters are identical to our adopted models. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\min }^{2}$ is marked with a cross. Contours are as in Figure 3.2.


Figure 3.8 Results for test galaxies fit with Geneva stellar evolution tracks-based models. All other parameters are identical to our adopted models. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\text {min }}^{2}$ is marked with a cross. Contours are as in Figure 3.2.


Figure 3.9 Results for test galaxies fit with models made with burst timescale $\tau_{2}=5 \times 10^{7}$, half the adopted duration. All other parameters are identical to our adopted models. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\text {min }}^{2}$ is marked with a cross. Contours are as in Figure 3.2.


Figure 3.10 Results for test galaxies fit with models made with burst timescale $\tau_{2}=2 \times 10^{8}$, twice the adopted length. All other parameters are identical to our adopted models. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\min }^{2}$ is marked with a cross. Contours are as in Figure 3.2.


Figure 3.11 Results for test galaxies fit with models made with age at merger, $t_{1}=12$ Gyr. All other parameters are identical to our adopted models. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\text {min }}^{2}$ is marked with a cross. Contours are as in Figure 3.2.


Figure 3.12 Results for test galaxies fit with models made with continuing uninterrupted (as opposed to truncated) progenitor star formation. All other parameters are identical to our adopted models. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\min }^{2}$ is marked with a cross. Contours are as in Figure 3.2.


Figure 3.13 Results for test galaxies fit with models made with continuing constant burst star formation, i.e. $\tau_{2}=\infty$. All other parameters are identical to our adopted models. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\text {min }}^{2}$ is marked with a cross. Contours are as in Figure 3.2.


Figure 3.14 Results for test galaxies fit with models made with a Scalo (1986) IMF. All other parameters are identical to our adopted models. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\text {min }}^{2}$ is marked with a cross. Contours are as in Figure 3.2.


Figure 3.15 Results for test galaxies fit with models made with a Scalo (progenitor) + Rieke (10) (burst) IMF. All other parameters are identical to our adopted models. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\min }^{2}$ is marked with a cross. Contours are as in Figure 3.2.


Figure 3.16 Results for test galaxies fit with models made with a Scalo (progenitor) + Rieke (11) (burst) IMF. All other parameters are identical to our adopted models. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{m i n}^{2}$ is marked with a cross. Contours are as in Figure 3.2.


Figure 3.17 Results for test galaxies fit with solar metallicity Kurucz atmospheres models. All other parameters are identical to our adopted models. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\text {min }}^{2}$ is marked with a cross. Contours are as in Figure 3.2.


Figure 3.18 Results for the four test galaxies fit with sub-solar metallicity Kurucz atmospheres models. All other parameters are identical to our adopted models. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\min }^{2}$ is marked with a cross. Contours are as in Figure 3.2.


Figure 3.19 Results for test galaxies fit with super-solar metallicity Kurucz atmospheres models. All other parameters are identical to our adopted models. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\text {min }}^{2}$ is marked with a cross. Contours are as in Figure 3.2.


Figure 3.20 Results for test galaxies fit with sub-solar metallicity progenitor + super-solar burst metallicity Kurucz atmospheres models. All other parameters are identical to our adopted models. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\min }^{2}$ is marked with a cross. Contours are as in Figure 3.2.


Figure 3.21 Best fit and residuals for reddening test. All spectra are on the same relative scale. Artificial galaxy spectra are created with $20 \%$ mass in a young burst, reddened as marked on each plot. The presence of young stars can be seen clearly with $A_{V}=2$ mag. Galaxy, model, and residual are plotted as in Figure 3.3.

## CHAPTER 4

## The Red Merger Subsample

It is immediately obvious from the spectra of the red merger subsample (Figure 2.6). that little if any ongoing star formation is occurring in any of these galaxies. We selected this red subsample on just this basis, to investigate the stellar populations in this poorly studied regime of star formation in mergers. We look for subtle signs of interaction-induced star formation in this sample by comparing them to a sample of morphologically normal elliptical and S0 galaxies. We use the EPS models and fitting technique developed in Chapter 3 to perform a detailed analysis of the stellar populations in the both the red merger and E/S0 control sample.

### 4.1. Results

Each galaxy spectrum was fit with the grid of EPS models by the procedure described in Chapter 3. The fitting results are shown in Figure 4.1 for the red merger sample and test galaxy and in Figure 4.2 for the control E/S0 sample. The results are also summarized in Table 4.1. The best fit for each galaxy, along with fitting residual, is over plotted on each spectrum in Figures 4.3 and 4.4. The
best fitting solution is quite good in all cases, with the largest residuals lying near $5100 \AA$ in some of the galaxies in the control sample, e.g. NGC 3941 and NGC 4626, the area where the red and blue ends of these spectra were joined. The continuum slope removed was rather high for both IC 162 and NGC 5866, though this slope would be consistent with reddened stellar population.

The red mergers show little recent star formation, with burst mass, $f_{b}$ between 1.2 and $6.3 \%$ and burst ages $t_{2} \sim 1$ Gyr. The detections of a young star burst in most of these galaxies is marginal, typically at the $2 \sigma$ level. However, even small bursts like these may be responsible for a nominal fraction of the galaxies' optical light, as illustrated by the solutions for NGC 474 and NGC 7585 in Figure 4.3. The best fit progenitor galaxies tend to be early-type galaxies, with star formation timescale $\tau_{1}=1-2$ Gyr for all galaxies except NGC 942/3. However, this parameter is not well constrained as evidenced by the large uncertainties in Table 4.1 and the $\chi^{2}$ contours in Figures 4.1 and 4.2. The S0 sample is very similar to the red mergers, while the elliptical sample seems to harbor still less star formation, with $f_{b} \leq 0.5 \%$.

The mean ages for both red merger and control galaxies are generally between 7 and 10 Gyr. Table 4.2 gives the mass limits on stars younger than 1 Gyr and 0.5 Gyr in columns 3 through 6 . The red merger sample has the highest amount of allowed star formation younger than 1 Gyr , where $0.2-3.2 \%$ of the galaxies' stellar masses can be in relatively young stars. The S 0 sample also has upper mass limits of $0.5-2.7 \%$, while the elliptical sample allows only a fraction of a percent. The minimum required star burst is consistent with zero in all cases. The range of allowed star formation histories is quite comparable for the red merger and S0 galaxies; however, there is a clear difference between the merger and elliptical
samples.

We showed in Chapter 3 that uncertainties resulting from our choice of IMF should be small in red galaxies like these. We also need to show whether this difference could be due to metallicity effects. We have calculated Mg2 indices (defined in Faber et al. 1985) for each of the galaxies from our integrated spectra. These are presented in Table 2.1. These Mg 2 indices differ from those listed by Davies et al. (1987), because their values are derived from nuclear spectra while ours come from integrated spectra, and the average metallicities of elliptical galaxies are lower than the metallicities of their nuclei. The correlation between the Mg 2 index and $[\mathrm{Fe} / \mathrm{H}]$ (Worthey et al. 1992) shows that on average, the metallicity of the galaxies in the elliptical sample are approximately solar or slightly greater. The red merger sample seems to be at comparable metallicity to the S 0 sample and slightly more metal poor than the elliptical sample. We therefore conclude that the similarity between the stellar populations in the red merger sample and the S 0 galaxies is likely to be real, but the difference between the red mergers and elliptical galaxies may be the result of metallicity effects.

Although there is little evidence for substantial reddening in these red mergers, we tested whether this could introduce additional uncertainty in our model fits. We reddened the models fit to the galaxy spectra with $A_{V} \propto M_{g a s} / M_{\text {stars }}$, where the mass of gas and stars were computed from the star formation history. This set of models is described more fully in Chapter 5. The burst masses derived from the reddened models were nearly identical to those derived from the unreddened models, for all physical solutions. This suggests that the stellar populations in the red mergers are unlikely to be significantly reddened.

Finally, we note that the family of acceptable solutions is degenerate in $f_{b}$ and
$t_{2}$. This is clearly illustrated in Figures 4.5 and 4.6 , where acceptable solutions (i.e. $\chi^{2}$ within $5 \%$ of $\chi_{\text {min }}^{2}$ ) for each galaxy are shown as dark areas in the $\left(f_{b}, t_{2}\right)$ plane. The older the star burst that is found, the more massive that star burst can be. This age-burst strength degeneracy is has been found in many other stellar population studies (Leonardi \& Rose 1996 and references therein), and our fitting method does not appear to break this degeneracy, at least for galaxies whose light is dominated by an old stellar population.

### 4.2. Notes on Individual Galaxies

### 4.2.1. The Mergers

NGC 474 NGC 474 is a shell galaxy with a strong but narrow $\mathrm{H} \alpha$ emission line, that arises from the nucleus of the galaxy (Baleisis et al. 1998). Our best fit shows it housed a burst of up to $5 \%$ of the galaxies mass a little more than 1 Gyr ago. For such a case about $1 / 3$ of the optical light is produced by the burst population. Some neutral hydrogen remains, about $10^{9} \mathrm{M}_{\odot}$, typical for an Sa or Sab galaxy.

Schweizer \& Seitzer (1992) derived a heuristic merger age for NGC 474 of about 5 Gyr. Direct comparison of our results is difficult, since we do not allow for burst greater than 1.5 Gyr old.

IC 162 IC 162 is a shell galaxy with a nearby, and possibly interacting companion. Our fitting results show little star formation is allowed in this galaxy in the last Gyr, but the galaxy has retained a fair amount of gas, again similar to that of a typical Sab galaxy. How the shells originated without disturbing this gas to induce star formation, is an intriguing question. Perhaps the shells in IC 162 are the result of a minor merger of a gas-poor companion, while the gas in the galaxy itself was
stabilized against nuclear inflow by its substantial bulge.

NGC 750/1 NGC 750 and 751 make up an interacting pair of elliptical galaxies with a tail of tidal debris. Their lack of recent star formation and higher metallicity are quite similar to the elliptical control sample we examined. It is somewhat surprising however, that they contain a substantial amount of gas with $\mathrm{M}_{\mathrm{HI}}=2 \times 10^{9} \mathrm{M}_{\odot}$, which makes them, along with IC 162 , the most gas rich objects in the red merger or red control sample.

NGC 942/3 NGC 942 and 943 make up another interacting pair of galaxies. NGC 942 has a clear dust lane and therefore is likely to be an early-type disk galaxy. The integrated spectrum shows weak $\mathrm{H} \alpha$ and [ O II] 3727 A emission. The best model fit for these galaxies describes a pair of spirals that had starbursts about 1 Gyr ago. It is worth pointing out that if this is indeed the case, the star burst would have occurred before or at the beginning of the gravitational interaction between this pair.

NGC 7284/5 NGC 7284 and 7285 , like NGC 942/3, is an interacting pair of galaxies that shows weak $\mathrm{H} \alpha$ and [O II] emission. NGC 7284 is a barred disk galaxy. The situation is similar to that of NGC $942 / 3$, our best fitting solution would put the time of the burst prior to strong gravitational interaction, and even our age limits allow bursts as recently as a few tenths of a Gyr. Up to $2 \%$ of the mass of the galaxy can be composed of stars formed within the last Gyr.

NGC 7585 NGC 7585 is an assymetric shell galaxy. Our best fitting model suggests it underwent a strong ( $6 \%$ by mass) about 1 Gyr ago. Spiral progenitors
are not ruled out for this galaxy, indicating a possible major merger origin for its shells. The upper limit on neutral hydrogen mass in NGC 7585 is not very restrictive at $10^{10} \mathrm{M}_{\odot}$, so some gas may remain. About $1 / 3$ of the optical light is contributed by the star burst population.

Schweitzer \& Seitzer (1992) find a heuristic merger age for NGC 7.585 of about 5-6 Gyr. As with NGC 474, it is difficult to compare with these results directly since our models do not allow for burst (merger) ages greater than 1.5 Gyr. McGaugh \& Bothun (1990) analyzed the colors of the shells and found them to be similar to the disk of an Sb galaxy and not blue enough for recent star formation. which taken with our results, seems to indicate that recent star formation. if any, was restricted to the nucleus and surrounding regions of the galaxy.

NGC 7727 NGC 7727 has the classically disturbed morphology indicative of two disk galaxies in the process of merging. However, it harbors no current star formation. Model fits show that the progenitors were likely to be earlier type than Sb , with a merger-induced burst occurring about 0.5 Gyr ago, involving up to $3 \%$ of the galaxy's mass.

### 4.2.2. Select Control Galaxies

NGC 3941 and NGC 5866 NGC 3941 and NGC 5866 are both S0 galaxies, and weak IRAS sources with $\mathrm{L}_{\text {FIR }} \approx 10^{9} \mathrm{~L}_{0}$. The best fits for both these galaxies are consistent with spiral galaxies with truncated star formation at a few $\times 10^{8}$ years ago. This is consistent with evolution of an S0 galaxy from a spiral when star formation ceases. However, the fits for NGC 3941 also allow a post-burst population of up to $3 \%$ of the stellar mass.

NGC 4889 NGC 4889 is the cD galaxy in the Coma cluster. Our best fit indicates that up to $5 \%$ of its optical light comes from a star burst slightly more than 1 Gyr old, and up to $1.5 \%$ of its stellar mass may be less than 1 Gyr. NGC 4889 is also quite metal rich. so solar metallicity models would tend to underestimate the amount of mass in young stars.

### 4.3. Discussion

At least four of the interacting galaxies appear to be dynamically young, with pairs of galaxies, and one more advanced merger, NGC iT2T with with similar morphology to NGC 7252, dynamically age dated at about 0.5-2 Gyr (Schweizer 1983). The dynamical age of the shell galaxies is more difficult to determine since shells may originate in either major or minor mergers. The burst ages we derive for most of the galaxies are consistent with their morphology except in two cases. For NGC 942/943 and NGC $7284 / 5$, the derived ages of approximately 1 Gyr seem to be inconsistent with pairs of galaxies just beginning their interaction. However. given the dynamical youth of these systems. their integrated spectra are likely to be dominated by evolved progenitor populations. Ages similar to these are also found in our morphologically normal control sample, which should be similar to the progenitor populations in NGC 942/943 and NGC $2284 / 5$.

If a merger is capable of generating star formation, the obvious question is why aren't these relatively young mergers forming more stars at the present time? There are several possibilities: (1) there was little gas in the progenitor galaxies to begin with, as might occur in an elliptical-elliptical or elliptical-S0 merger, or (2) the gas in the progenitor galaxies did form stars which have since faded to the point where the optical spectrum is dominated by the stars in the progenitor
population, or (3) a gas-rich progenitor galaxy merged. formed few new stars, and remains gas rich. Possible examples for all three scenarios can be found from the notes on individual galaxies, for (1) NGC $750 / 1$. (2) NGC 474 or NGC 7.585 , and (3) IC 162.

Dynamical timescales of the morphological features might in principle be used to choose between these scenarios. The first scenario above is probably most likely in the case of interacting, but yet unmerged pairs since their star formation rate should be dominated by their pre-interaction star formation pattern. Most difficult to place are the shell galaxies, since shells resulting from a minor merger form within 0.25 Gyr (Hernquist \& Quinn 1988) but form in a major merger at about 2 Gyr (Hernquist \& Spergel 1992). If the shells result from minor mergers the first scenario is again probably most likely, but shells resulting from major mergers could be the result of any of the three scenarios. If the shells were indeed formed in a major merger and are $\gtrsim 2$ Gyr old, the second scenario is increasingly likely. as may be the case in NGC 474 and NGC 7585.

Several of the red mergers have upper limits of about $3 \%$ of their mass in stars younger than 1 Gyr. We note that in an $L_{=}$galaxy, a star burst of this size is is a major event. In Figure 4.7. we show the evolution of the bolometric luminosity of a star burst with a mass of $10^{10} \mathrm{M}_{\odot}$ and an exponentially decaying SFR with $\tau=10^{8} \mathrm{yr}$. At peak luminosity, near $t \sim 5 \times 10^{7} \mathrm{yr}$, this star burst has a bolometric luminosity of approximately $4 \times 10^{11} \mathrm{~L}_{\odot}$, which if reprocessed by dust and emitted in the far infrared, would make the parent galaxy an luminous infrared galaxy, or with a factor of 2 more mass, an ULIRG. Star bursts of this size are not required by the EPS fitting solutions, but also cannot be ruled out, as the luminosity fades by a factor of 30 by age $t_{2} \sim 1$ Gyr.

### 4.4. Summary and Conclusions

In summary, we have fit EPS models of different ages and galaxy types to the integrated spectra of a sample of mergers with early-type spectra and to a control sample made up of elliptical and S0 galaxies. We find that:

- A significant fraction of galaxies in a morphologically selected sample of mergers and interacting galaxies have integrated spectra resembling those of early-type galaxies.
- The stellar populations implied by the spectra of the red merger sample are indistinguishable from those in a control sample of SO galaxies. Small differences in the upper limits on recent star formation between these mergers and a sample of elliptical galaxies may be due to metallicity effects.
- The minimum amount of star formation required in the last 1 Gyr is consistent with zero for all of the red merger and the $\mathrm{E} / \mathrm{S} 0$ samples.
- The maximum amount of new star formation allowed ranges from 0.2-3.2\% by mass in the merger sample and $0.0-2.7 \%$ in the $E / S 0$ control sample. A star burst of $3 \%$ of the stellar mass of an $L^{*}$ galaxy would require that galaxy to pass through a luminous infrared galaxy phase about 1 Gyr ago.

Table 4.1. Red Galaxies-Best Fits

| Galaxy | $\chi_{\min }^{2}$ | $\tau_{1}$ | $t_{2}$ | $f_{b}(\%)$ |
| :--- | :---: | :---: | :---: | :---: |
| NGC 474 | 1462 | $1 \pm 2.4$ | $9.1 \pm 0.3$ | $5.1 \pm 6.5$ |
| IC 162 | 2174 | $1 \pm 0.5$ | $7.6 \pm 0.5$ | $0.0 \pm 0.0$ |
| NGC 750/1 | 1266 | $<2^{*}$ | $>7.0^{*}$ | $<0.1^{*}$ |
| NGC 942/3 | 1318 | $14 \pm 14.0$ | $9.1 \pm 0.2$ | $1.0 \pm 0.6$ |
| NGC 7284/5 | 1496 | $2 \pm 7.1$ | $8.9 \pm 0.4$ | $0.9 \pm 0.6$ |
| NGC 7585 | 967 | $1 \pm 9.3$ | $9.1 \pm 0.4$ | $6.2 \pm 4.7$ |
| NGC 7727 | 1021 | $2 \pm 3.9$ | $8.6 \pm 0.5$ | $0.3 \pm .5 .0$ |
|  |  |  |  |  |
| Art. Gal. | 724 | $2 \pm 3.5$ | $8.9 \pm 0.1^{*}$ | $7.1 \pm 5.5$ |
|  |  |  |  |  |
| NGC 3379 | 1140 | $<2^{*}$ | $7.0 \pm 1.0^{*}$ | $<0.1^{*}$ |
| NGC 4472 | 891 | $1 \pm 0.9$ | $>9.0^{*}$ | $0.0 \pm 0.1$ |
| NGC 4648 | 1547 | $<2^{*}$ | $>7.5^{*}$ | $<0.2^{*}$ |
| NGC 4889 | 2107 | $1 \pm 7.1$ | $8.9 \pm 1.5^{*}$ | $0.9 \pm 0.4$ |
|  |  |  |  |  |
| NGC 3245 | 1229 | $<2^{*}$ | $>7.0^{*}$ | $<1.0^{*}$ |
| NGC 3941 | 1641 | $3 \pm 6.5$ | $8.6 \pm 0.7$ | $<3.0^{*}$ |
| NGC 4262 | 22.54 | $1 \pm 5^{*}$ | $>8.4^{*}$ | $<5.0^{*}$ |
| NGC 5866 | 832 | $2 \pm 0.6$ | $<8.2^{*}$ | $0.0 \pm 0.2$ |
|  |  |  |  |  |

*Uncertainties or limits derived by eye from contour plot.

Table 4.2. Red Galaxies: Limits

| Galaxy | $<$ age $>$ |  | Max \% |  | Min \% |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $<1 \mathrm{Gyr}$ | $<0.5 \mathrm{Gyr}$ | $<1 \mathrm{Gyr}$ | $<0.5 \mathrm{Gyr}$ |  |
| NGC 474 | $9.8_{-3.4}^{+0.0}$ | 2.69 | 0.47 | 0.00 | 0.00 |  |
| IC 162 | $9.0_{-0.2}^{+0.2}$ | 0.16 | 0.16 | 0.02 | 0.02 |  |
| NGC 750/1 | $9.1_{-0.7}^{+1.5}$ | 0.24 | 0.04 | 0.00 | 0.00 |  |
| NGC 942/3 | $6.8_{-0.4}^{+3.0}$ | 2.66 | 0.24 | 0.00 | 0.00 |  |
| NGC 7284/5 | $8.8_{-2.0}^{+1.3}$ | 1.9 .5 | 0.34 | 0.00 | 0.00 |  |
| NGC 7585 | $9 . i_{-3.2}^{+0.0}$ | 3.17 | 0.46 | 0.02 | 0.00 |  |
| NGC 7727 | $8.4_{-1.7}^{+1.4}$ | 2.80 | 0.51 | 0.02 | 0.00 |  |
|  |  |  |  |  |  |  |
| Art. Gal. | $8.3_{-2.4}^{+0.9}$ | 8.59 | 1.31 | 3.71 | 0.36 |  |
|  |  |  |  |  |  |  |
| NGC 3379 | $9.0_{-0.0}^{+0.2}$ | 0.07 | 0.06 | 0.01 | 0.01 |  |
| NGC 447. | $10.6_{-1.0}^{+0.0}$ | 0.00 | 0.00 | 0.00 | 0.00 |  |
| NGC 4648 | $9.2_{-0.7}^{+1.4}$ | 0.24 | 0.04 | 0.00 | 0.00 |  |
| NGC 4889 | $9 . i_{-1.9}^{+0.4}$ | 1.47 | 0.25 | 0.00 | 0.00 |  |
|  |  |  |  |  |  |  |
| NGC 3245 | $9.0_{-0.0}^{+1.4}$ | 0.49 | 0.12 | 0.00 | 0.00 |  |
| NGC 3941 | $7.8_{-1.0}^{+2.0}$ | 2.65 | 0.25 | 0.00 | 0.00 |  |
| NGC 4262 | $9.6_{-2.5}^{+0.5}$ | 1.58 | 0.29 | 0.00 | 0.00 |  |
| NGC 5866 | $8.1_{-0.0}^{+1.1}$ | 0.48 | 0.24 | 0.06 | 0.05 |  |



Figure 4.1 Fitting results for the red merger sample. Burst age, $t_{2}$, is plotted against progenitor type $\tau_{1} \cdot \chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\text {min }}^{2}$ is marked with a cross. $\chi^{2}$ is contoured at $(1.05,1.1,1.2,1.5,2,5$, $10,20,50) \chi_{\min }^{2} . f_{b}$ is contoured at $(0.1,0.2,0.5,1,2,5,10,20,50,100)$ percent total stellar mass fraction.


Figure 4.2 Fitting results for the E/S0 control sample. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\text {min }}^{2}$ is marked with a cross. Contours are as in Fig. 4.1.


Figure 4.3 Best fitting models and residuals for the red merger sample. The emission line-cleaned galaxy spectrum is plotted as a series of points, the best fit model is plotted as a solid line, the progenitor populations as a dashed line, the burst population as a dotted line, the continuum contribution as a long-dashed line, and the residual is plotted as a dot-dashed line.


Figure 4.4 Best fitting models and residuals for the E/S0 control sample. Galaxy, models, and residuals are plotted as in Figure 4.3.


Figure 4.5 Age vs. mass for allowed star bursts in the red merger sample. Dark areas represent regions of acceptable solutions. There is a clear age-mass degeneracy.


Figure 4.6 Age vs. mass for allowed star bursts in the E/S0 control sample. Dark areas represent regions of acceptable solutions. NGC 3379 and NGC 4472 had no acceptable solutions with $f_{b} \geq 0.1$


Figure 4.7 Evolution of the bolometric luminosity of a $10^{10} \mathrm{M}_{0}$ star burst with exponentially decaying star formation with $\tau=10^{8} \mathrm{yr}$. From GISSEL96 (Bruzual \& Charlot 1998) models. The bar at $\log L=11$ represents the range of $L$ allowed in the red merger sample, assuming a stellar mass-to-light ratio of 5 , the $M_{B}$ values for each galaxy given in Table 1. and a young burst mass fraction of $3 \%$.

## Chapter 5

## The Blue Merger Subsample

The spectra of the blue merger subsample are quite diverse, with the only criteria in their selection to this subsample being moderate to strong $\mathrm{H} \alpha$ emission. indicating ongoing star formation, or blue stellar continuum. This blue merger sample contains interacting spirals, advanced mergers with weak star formation. $\mathrm{E}+\mathrm{A}$ or postburst galaxies, and mergers containing intense star bursts. In this chapter. we investigate the stellar populations of this group of galaxies, along with those of a similarly diverse control sample of spirals of types from Sa to Magellanic irregulars plus the $[0$ starburst galaxy, $M 82$. To that end, the spectra from these galaxies were fit with the EPS models and fitting procedure developed in Chapter 3. To further explore the range of star formation properties and the difference between the merger and control samples, we have measured several spectra features, including line indices, equivalent widths, and continuum color.

### 5.1. Results

### 5.1.1. The Unreddened Models

The results of fitting the grid of EPS models to each merger spectrum are shown in Figures 5.1 through 5.3, and summarized in Tables 5.1 and 5.2. The best fit models and residuals are shown in Figures 5.4 through 5.6. The fits for all galaxies are reasonable, with the largest residuals occurring around the $\mathrm{H} \gamma$ absorption feature and for two of the galaxies with spectra from LK95, NGC 1222 and NGC 7252, near the $5100 \AA$ joining point of the red and blue ends of the spectra.

The blue mergers have a wide range of progenitor types, and this parameter, $\tau_{1}$, is much better constrained than for the galaxies in the red merger subsample. The progenitor type is typically less well constrained when the burst population dominates the optical spectrum, or when the merger is old enough ( $\gtrsim 0.5 \mathrm{Gyr}$ ) for the differences in progenitor populations to be minimal due to the truncation of star formation and subsequent passive evolution. The blue sample also has a wide range of burst ages, from about 20 Myr to 1 Gyr. Younger bursts tend to have less mass, but to some extent this makes sense. Bursts 50 Myr old or younger are less than one e-folding time into the starburst and a considerable mass fraction should remain in gas. This may also be a consequence of dust content since younger bursts tend to be more highly reddened.

The amount of mass in stars younger than 1 Gyr is reasonable for most galaxies, with only four mergers with the young mass fraction of more than $1.5 \%$. The best fits for these four galaxies, NGC 3921, NGC 4676, NGC 5278/9, and NGC 7252 have four of the five largest $\chi^{2}$ values in the sample, indicating poor fits or lower signal-to-noise. In particular, the fits for NGC 4676 and NGC $5278 / 9$ place
almost no constraints on the stellar populations in these galaxies. The lower mass limits are less than $10 \%$ for all galaxies in the sample. This is within reasonable physical limits for spiral galaxies which can have up to about $1.5 \%$ of their mass in gas. The results for NGC 3303 are consistent with no recent star formation. and NGC 3656 nearly so. with and upper limit of $1.6 \%$ and a lower limit of a fraction of a percent.

A relatively small number of blue merger galaxies show evidence for a burst of at least a few percent of their mass when dust is not accounted for. These are NGC 2623. NGC 3448. NGC 3921, NGC 4194. IC 883. and NGC 7252. The 1.5 remaining blue mergers have burst strengths that are consistent with zero and limits of burst masses of less than $1 \%$. Of these galaxies, six are unmerged but interacting pairs, which may not have undergone a major starburst. Three others are LIRGs or ULIRGs. NGC 1614. NGC 2782, and Arp 220, suggesting dust may be obscuring most of any star burst they contain. Two others. .VGC 3303 and NGC 3656. show little evidence for any recent star formation. Extinction may play a role in obscuring a starburst in the remaining galaxies as well. The other alternative, that the interaction and merger of the galaxies triggered either a weak star burst or none at all, is clearly not the case for many of these galaxies, where far-infrared luminosities indicate that significant starbursts are occurring.

The fitting results for the spiral control sample are shown in Figures $5 . \bar{i}$ through 5.9 and summarized in Tables 5.3 and 5.4. The best fit models and residuals are shown in Figures 5.10 through 5.12. Again, the fits to these galaxies are reasonable, with some residuals showing features around $5100 \AA$ where the $K 92$ spectra were joined together. This is somewhat surprising, since the burst model of star formation history is not appropriate for most of these galaxies.

The results return progenitor types, $\tau_{1}$, that are roughly consistent with the spirals' morphological types. Burst masses are generally consistent with zero. except at very late type spirals and Magellanic irregulars. Mass limits on young ( $<1 \mathrm{Gyr}$ ) stars restrict these to no more than $1.5 \%$ of the mass in every galaxy in the control sample. The required mass in young stars increases as galaxies go to later progenitor types. The exception to this is the dwarf galaxy NGC 1569, which has a fairly red continuum in spite of strong emission lines.

While most of the spirals show evidence for young stars. few show clear evidence of a recent burst. Exceptions to this include NGC 2276 and NGC 4775. Sc galaxies, NGC 4631, an Sc galaxy which may have a starburst nucleus (Golla \& Wielebinski 1994), NGC 4449 and NGC 4485, Magellanic irregulars, and NGC 4670, a peculiar SB galaxy. This shows that active. ongoing star formation may be difficult to distinguish between a discrete starburst event.

Finally, the fitting results for the unreddened models for both the blue merger and spiral control sample show a strong degeneracy in burst age and burst mass. in the sense that an older, stronger burst can produce the same acceptable fit as a younger weaker one. This is illustrated in Figures 5.13 through 5.18. This is the familiar age-strength degeneracy (Leonardi \& Rose 1996 and references therein). In principle, it may be possible to break this degeneracy using other data, for example with $L_{F I R} / L_{B}$, supernovae rates derived from shock-excited emission lines. or number of ionizing photons. However, optical data is not well suited for this due to the heavy obscuration of star forming regions, along with differential reddening problems. In addition, the $\mathrm{H} \alpha$ and other emission lines may be contaminated by AGN contributions.

### 5.1.2. Description of the Reddened Models

Unlike the red merger sample, the presence of dust in the blue merger sample is a significant source of uncertainty in the burst masses derived from our fitting procedure. We showed in Section 3.3.6 that an extinction of $A_{V}=1 \mathrm{mag}$ can reduce the burst mass required by an order of magnitude. Many of the galaxies in the blue merger sample are known to be highly reddened. Optical depths in the arms of spiral galaxies can reach $\tau_{V} \sim 4$ (Rix \& Rieke 1993). Dust lanes are apparent in many of the galaxy images in Figures 2.3 through 2.5, and several. NGC 1614, NGC 2623, Arp 195, NGC 2782, IC 883, NGC 6621/2, and Arp 220 are luminous infrared galaxies (LIRGs) or ULIRGs indicating the presence of a large amount of dust. In addition, $A_{V}$ has been estimated for several galaxies using a simple foreground dust screen model, and can be similarly estimated for several others, using the $H-K$ data of Bushouse \& Stanford (1992). These are given in Table 5.5 for a subsample of the blue mergers. Several magnitudes of extinction are possible, with values as large as $A_{V}=12.3 \mathrm{mag}$ for the primary nucleus of NGC 520 and 10 mag for the entire body of Arp 220 . The nuclei of Arp 220 are completely obscured even in the near-infrared, with measured values of $A_{v}$ up to 24 mag from NICMOS near-infrared images, and $A_{V} \sim 50$ from ISO measurements of mid-infrared emission lines (Scoville et al. 1998, Sturm et al. 1996. respectively). It is important to note that extinctions derived from optical spectra by Liu \& Kennicutt (199.5a) are considerably smaller than those derived from near-infrared data. This suggests that optical and infrared data sampling very different stellar populations as some regions are completely obscured in the optical.

Since it is not possible to solve for the reddening directly with the fitting procedure outlined in Chapter 3, we attempt to quantify the uncertainty by
reddening the models themselves. Reddening is a complicated function of the amount of dust, type of dust grains, and geometry of a system, and the proper model is likely to be different for each galaxy. Complicating matters further is the fact that different measures of reddening, such as the Balmer decrement and near-infrared colors, give discrepant values for the reddening in these galaxies (see Table 5.6). Finally, the reddening in a galaxy should decrease as it ages and gas and dust is consumed, ejected, or destroyed. Taking this last factor into account, we have reddened the EPS models according to one of two simple prescriptions. The first assumes that the extinction is proportional to the density of the dust, and with constant gas-to-dust ratio and dust volume this gives,

$$
A_{V} \propto M_{g a s}
$$

where $M_{g a s}$ is the remaining gas mass in the burst and can be calculated from the star formation history of the burst. The second reddening prescription assumes that the extinction goes as the ratio density of the dust to the density of the stars. This might be expected if stellar radiation and supernova shock wave contribute to the destruction of dust grains. With the same assumptions as above, this gives,

$$
A_{V} \propto M_{g a s} / M_{\text {stars }}
$$

where again the stellar mass can be calculated given the star formation history of the starburst.

We calculate the constant of proportionality by making use of the optical depth in Sc galaxies, $\tau_{B} \approx 0.8$, found by Wang et al. (1996), assuming the optical depth ratio, $\tau_{B} / \tau_{V}=4 / 3$, that an Sc galaxy is appropriately represented with a star formation decay timescale of $\tau_{1}=10$, and making note of the fact that $A_{V}=0.92 \tau_{V}$, where $\tau_{V}$ is the optical depth at $V$. The resulting values of $A_{V}$
are given in Table 5.6. For simplicity, the models were reddened using a simple foreground screen dust model, and reddenings for the progenitor population were held fixed at their values at the time of the burst, $t_{2}=0$. The actual physical situation is much more complicated, with extinction being a function of the geometry of the system, including mixture of dust and stars, differential reddening among populations, and viewing angle.

The second set of models $\left(A_{V} \propto M_{g a s} / M_{s t a r s}\right)$ is more heavily reddened at young ages and late type progenitors than the first set of models $\left(A_{V} \propto M_{g a s}\right)$, although the second set of models remains reddened for a longer period of time. For simplicity, we refer to the second set of models as the highly reddened case. We refit all galaxy spectra with these two sets of reddened models. In most cases the burst age found does not change with the reddening model assumed. This result is as expected from the reddening test in Section 3.3.6, where the input burst age was recovered.

It is important to emphasize that by fitting these reddened models to the galaxy spectra we are attempting to quantify the uncertainty in the burst mass found, due to the presence of dust. With extinctions as high as $A_{V}=8.7$ for a $10^{7} \mathrm{yr}$ starburst in the highly reddened case, the changes in burst mass found can be more than an order of magnitude. Since the burst mass found is extremely sensitive to the reddening, it is unwarranted to chose one solution as the definitive one, and we present all burst masses found to illustrate the range of uncertainty present.

### 5.1.3. Fitting Results for the Reddened Models

The grids containing the reddened model fitting results for eight representative galaxies from both the merger and control samples are shown in Figures 5.19 and 5.20. Burst masses found for all three sets of models are given in Tables 5.7 and 5.8. The fits to all galaxies are reasonable for the reddened models, with the largest residuals occurring around the $\mathrm{H} \gamma$ absorption feature, and for two of the galaxies with spectra from LK95, NGC 1222 and NGC 7252 , near the $5100 A$ joining point of the red and blue ends of the spectra. The fitting residuals for the reddened models are very similar to those of the unreddened models, even to the details of the residual structure. and so are not shown.

The burst ages required are relatively insensitive to which reddened models are used to fit the galaxy; about $1 / 3$ of the galaxies have ages which increase slightly when the model populations are reddened. The burst ages may be insensitive to reddening because both truncation of progenitor star formation and onset of the interaction-induced burst occur at the same time in our assumed star formation history. Even when one population is completely dominating the spectrum. the age found is likely to be the same.

The fits for the unreddened models require burst masses that are consistent with zero for most galaxies, including some like NGC 520 and $\operatorname{Arp} 220$ which are known to harbor starbursts. With very high extinction in these galaxies most of the light from the burst is almost completely obscured. The reddened models give results that include burst mass fractions of typically a few percent for most galaxies. The difference between the two different reddening models is quite small for most galaxies, with the exceptions of NGC 520, Arp 195, NGC 2782, NGC 3656, Arp 220 , and NGC 7252 . These galaxies all have high global extinctions, with $A_{v}>3$
mag (see Table 5.5) or high far-infrared luminosities indicating a large amount of dust.

With the adjustment from the reddened models, most galaxies have upper limits on the burst mass of $20 \%$ or less. This is close to the maximum amount of gas most normal spiral galaxies contain and therefore is a hard upper limit on the amount of star formation which can occur. Three galaxies, NGC 3921, NGC 4676, and NGC $5278 / 9$ have upper limits of $100 \%$. These galaxies have the three poorest fits of any acquired with a single grating setting, and none of their parameters are well constrained. These three galaxies also contain AGN; NGC 3921, NGC 4676a, and NGC 4676b have LINER nuclei, while NGC 5278 and NGC 5279 both have Seyfert nuclei (Dahari 1985, Keel et al. 1985). It is possible that these AGN could be contributing enough continuum to skew the fit to higher burst masses. These high masses come from bursts with ages of 1 Gyr or more. The lower limit on burst mass is $<7 \%$ for every galaxy in the blue merger sample, even in the highly reddened case. This is the least amount of star formation required by the fits and is well within the limit imposed by the amount of gas in their progenitor galaxies.

The lower limit on the burst mass in the control sample also correlates roughly with galaxy type, earlier type galaxies having fewer young stars. The burst mass found for the control sample changes dramatically with the reddening prescription employed. When $A_{V} \propto M_{g a s}$, the upper limit on the burst fraction, is less than for most galaxies. However, when $A_{V} \propto M_{g a s} / M_{\text {stars }}$, many of the control galaxies, even of types Sa and Sb , return burst masses of more than $10 \%$ and even more than $20 \%$ of their stellar mass. These burst masses are clearly unphysical, indicating the highly reddened burst models or perhaps the star formation histories are inappropriate for normal spiral galaxies.

There are several galaxies in the control sample to which our assumed star formation history should be appropriate. These are the Magellanic irregulars, NGC 1569, NGC 4449, and NGC 4485, and the nearby starburst galaxy, M82. The fits to the Sm galaxies all give relatively small burst masses, with $f_{b}<1.5 \%$ even in the most highly reddened cases. M82 fares somewhat better, with an upper limit of $f_{b}$ of $44 \%$. This result is surprising since these galaxies were thought to be dominated by young stars. However, as can be seen in the upper left panel of Figure 3.21, even a moderately aged burst of 0.2 Gyr making up $20 \%$ of a galaxy's mass completely dominates the optical spectrum; such a burst contributes more than $90 \%$ of the optical light in the unreddened case. Figure 3.21 contains no noise sources, so in an actual galaxy the amount of light and therefore of mass in a pre-existing population would be much harder to pinpoint. The extreme differences in the mass-to-light ratios of the two populations could increase the uncertainty in the mass found, with reddening only compounding the problem. Alternatively. if the consequences of such extremely different mass-to-light ratios was not fully appreciated, these galaxies may contain more old stars than previously believed. Given the difficulties in determining burst mass using this fitting method with optical data only, the more likely explanation is perhaps the former.

In Figure 5.23, the best fitting burst age for all galaxies is plotted against the highest burst mass allowed by the models. Overplotted are lines for burst masses of $5 \%$ of the stellar mass, "dereddened" by the extinction assumed in the models, the dotted line representing the highly reddened models. There is a clear relationship between the upper limit on burst mass and reddening model used. This shows that the burst mass found is a sensitive function of reddening model.

Finally, the fitting results for the unreddened models for both the blue merger
and spiral control sample showed a strong degeneracy in burst age and burst mass (Figures 5.13 through 5.18). However, just as burst mass is extremely sensitive to reddening, so is this degeneracy. Figures 5.21 and 5.22 illustrate this. The burst mass increases as reddening does, so in some cases there is actually a reversal of this degeneracy, illustrated most clearly in this subsample by NGC 520. More data is needed, particularly near-infrared data, to break this degeneracy, and detangle the effects of reddening.

### 5.2. Notes on Individual Galaxies

### 5.2.1. Selected Mergers

NGC 520 NGC 520 is a pair of galaxies at an intermediate stage of merging. The two progenitor components are still discernible within the merger (Stanford \& Balcells 1990). It has a prominent dust lane and a large $\mathrm{L}_{\text {FIR }}$ of just under $1^{11} \mathrm{~L}_{6}$. It has an $E+A$ type spectrum, and a neutral hydrogen gas mass typical of the Sc galaxies in our control sample. We find a burst age of $t_{2}=10$ to 200 Myr . Our reddened models show NGC 520 may harbor a burst of up to $14.2 \%$ of its stellar mass, although this value is quite uncertain due to the large amount of extinction in the galaxy, $A_{V} \lesssim 12 \mathrm{mag}$.

NGC 1222 NGC 1222 is the only galaxy in our sample that is not drawn from the Arp atlas (1966). It consists of three apparently interacting bodies, no discernible tidal features, and a main body with a smooth, almost elliptically shaped morphology. This galaxy is best fit by Sbc progenitors, with a burst age $<10^{8} \mathrm{yr}$ and compromising $<8.5 \%$ of the remnant's stellar mass. The smooth morphology and roughly elliptical contours of this galaxy do not seem to be
consistent with a young burst, however. H $\alpha$ emission is concentrated in the main nucleus and the eastern knot (Baleisis et al. 1998).

NGC 3303 NGC 3303 is an advanced merger with a tidal tail. Its integrated spectrum has a red stellar continuum, like the red galaxy subsample, but it also has strong $\mathrm{H} \alpha$ and [O II] $3727 \AA$ emission. Our results for this galaxy are much like those of the red sample; we find the progenitor type is not well constrained, with a burst age of $\sim 1 \mathrm{Gyr}$ and $<6 \%$ of the stellar mass.

NGC 3921 NGC 3921 has an integrated spectrum with blue stellar continuum and weak $\mathrm{H} \alpha$ and [O II] emission. The image shows it is an advanced merger with a relatively smooth body and tidal tails. It has a large amount of HI gas, $10^{10} \mathrm{M}$ © and $L_{F I R}=10^{10} L_{\odot}$. Our fitting results show that $N G C 3921$ contains a star burst of $>6.1$ \% of the galaxy's stellar mass, with age $0.5-1$ Gyr. This age seems consistent with the advanced morphological state of the merger.

NGC 4194 NGC 4194 is a merger in an advanced state, with some tidal debris and a shell-like structure on its southern edge. Its integrated spectrum shows very strong line emission, with Balmer emission seen to $\mathrm{H} \gamma$, and blue stellar continuum. It is a strong IRAS source with $L_{F I R}=5 \times 10^{10} \mathrm{~L}_{\odot}$, but only a relatively small amount of neutral hydrogen remains. Our best fit models suggest that NGC 4194 resulted from a merger of Sb or later type galaxies. However with a luminosity of $M_{B} \sim-20, \mathrm{Sb}$ type progenitors are probably ruled out. NGC 4194 experienced a burst of star formation contributing 1 to $5 \%$ to the stellar mass of the galaxy about $2 \times 10^{8} \mathrm{yr}$ ago. The mass we find for the burst in this galaxy is relatively independent of the reddening prescription we use; however, the age is tightly
constrained where the optical depth calculated from the star formation history is less than 1 .

NGC 4676 NGC 4676, a.k.a. the Mice. is a pair of interacting spiral galaxies which have tidal features. Our integrated spectrum is of lower signal-to-noise than the rest of the galaxies in the sample, but clearly shows H II region type line emission. Dust is clearly visible in the image. Unfortunately, our model fits do little to constrain the stellar populations in this pair of galaxies. Our best fit suggests a 1 Gyr old star burst which would seem to be inconsistent with an interaction-induced star burst judging from the morphology of the system. A higher signal-to-noise spectrum is required to put better constraints on the stellar populations.

IC 883 IC 883 is a LIRG in an advanced state of merging. displaying a morphologically disturbed main body and two tidal tails. Its integrated spectrum shows classic E+A features, with strong Balmer absorption and metal lines. Our best fit to IC 883 suggests this galaxy underwent a star burst about 0.5 Gyr ago that added about $4-6 \%$ to the stellar mass of the galaxy. The progenitor type is not well constrained. About half of the galaxy's optical light results from the star burst. This star formation history is consistent with the morphology, and suggests that IC S83 may have been an ULIRG a few hundred Myr ago. Like NGC 4194, the burst age of IC 883 is tightly constrained and the mass limits we find are largely independent of the reddening prescription we choose.

Arp 220 Arp 220 is an ULIRG. Morphologically, it consists of a single main body, with tidal debris and a strong dust lane. Its $K$-band surface brightness
profile follows an $r^{1 / 4}$ law to several Kpc (Wright et al. 1990). About $4 \times 10^{10} \mathrm{M}_{6}$ of neutral hydrogen remains in the galaxy, suggesting the galaxy's star burst is not yet dying out. The extinction towards the nuclei of this galaxy is extremely high, $A_{V}>10$ mag. The mass of the star burst is extremely sensitive to the reddening model we chose, with upper limits of L.3. 3.8, and $38.5 \%$ as $A_{V}=0, A_{V} \propto M_{g a s}$, and $A_{V} \propto M_{g a s} / M_{s t a r s}$, respectively. The age of the burst is not well constrained with $\log t_{2}=7.5 \pm 0.7$ Our models also suggest that the progenitors for this merger were of type Sb .

NGC 7252 NGC 7252 is the proto-typical merger. It has a single main body, morphologically disturbed but with an underlying $r^{1 / 4}$ law profile typical of an elliptical galaxy, as well as two long tidal tails (Schweizer 1982). Our models suggest that NGC 7252 underwent a burst of star formation approximately 0.5 Gyr ago that added up to $20 \%$ of the stellar mass of the galaxy, depending on the reddening model chosen. The progenitor types are unconstrained. Approximately $1 / 2$ of the galaxy's optical light is contributed by the star burst population. Still a strong FIR source with $L_{F I R}=3 \times 10^{10} \mathrm{~L}_{6}$, it is likely that NGC 7252 underwent an ULIRG phase a few hundred Myr ago.

### 5.2.2. Selected Control Galaxies

We describe the results of several galaxies in the control sample to explore the range of results we can expect from out fitting procedure. At one extreme is NGC 1832, a normal Sb galaxy where fitting the burst-type star formation history gives unphysical results, and at the other M82, which is the well-known starburst galaxy, where our star formation history is completely appropriate.

NGC 1832 NGC 1832 is a normal SBb galaxy, without a starburst nucleus (Devereux 1989). Our best fitting models suggest a "progenitor type" of Sb-Sc. which is in good agreement with the morphological type. The fitting solutions, forced to pick a burst age, find $\log t_{2}=7.5 \pm 0.6$. The mass varies considerably with the reddening chosen for the burst, with unreddened and lightly reddened models give burst masses of $<2 \%$, and heavily reddened models allowing starbursts of up to $38.5 \%$ of the stellar mass of the galaxy. Starbursts of this magnitude are clearly not observed in NGC 1832, showing the uncertainty that inappropriate star formation history and reddening models can add to the solutions of a galaxy.

NGC 2903 NGC 2903 is a starburst galaxy (Wynn-Williams \& Becklin 1985). of morphological type Sc. The fitting results for this galaxy give the highest upper limits on burst mass in the control sample. Our best fitting models show a progenitor type of $\mathrm{Sa}-\mathrm{Sb}$ and a burst age of $10-100 \mathrm{Myr}$. The fitting results are quite sensitive to reddening prescription with burst mass upper limits of 0.6, 1.5. and $46.2 \%$, for the unreddened, moderately reddened, and highly reddened models. respectively.

NGC 1569 NGC 1569 is a dwarf Sm galaxy with extremely active star formation. Its integrated spectra has $\mathrm{H} \alpha+[\mathrm{N}$ II $]$ emission with an equivalent width of 20.2 A (Kennicutt 1992a), although the stellar continuum is quite red, but with few absorption lines. This indicates a very young burst, dominated by 0 and $B$ stars. which is highly reddened. Our best fitting models give a progenitor type earlier than Sab, burst age of $12-90 \mathrm{Myr}$, and burst mass of less than $14 \%$. even in the most heavily reddened case. The burst mass seems quite small for such an active dwarf galaxy, but the starburst in NGC 1569 has been dated at about 10 Myr by
several other techniques (Delgado et al. 1997 and references therein).

M82 M82 = NGC 3034 is the well-known nearby starburst galaxy. Its fitting results are quite similar to those of NGC 2903. We find a progenitor type of $\mathrm{Sab}-\mathrm{Sc}$ and best fitting burst age of 10 Myr with an upper limit of 100 Myr . Again burst mass upper limits are highly reddening dependent at 0.8 .1 .3 , and $44.1 \%$ for the unreddened, moderately reddened, and heavily reddened cases, respectively. For comparison Mcleod et al. (1993) find an upper limit on the burst mass of about $50 \%$ of the stellar mass, in the nucleus of the galaxy. They also find a maximum extinction toward the stars of $A_{V}=12.5 \mathrm{mag}$, suggesting the highly reddened case may be warranted for this galaxy.

### 5.3. Comparisons with Previous Work

The stellar populations in many of these galaxies have been analyzed by other groups. A comparison of these analyses to ours is presented in Table 5.10. Some care is needed in these comparisons as the data type, region(s) under analysis. and method of analysis differ considerably between studies. The notes for Table 5.10 in Column 6 include a brief note of the method used to analyze the stellar populations (if not EPS), whether the analysis refers to the nucleus of the galaxy only, and if it was made from near-infrared data as opposed to optical data. However, with these caveats in mind a general comparison can be made. In general, the progenitor types in these mergers are not well constrained by our models, but are not in serious disagreement with those previously reported. Our burst masses are often inconsistent with those found by other investigators, which are inconsistent among themselves. Burst masses we find do tend to be in reasonable agreement with those
found by other investigators using optical data. The reasons for these variations in burst mass may be two-fold. First, all the near-infrared analyses of which we are aware are limited to nuclear data. If the spatial distribution of the stellar populations is not uniform, e.g. a starburst is concentrated in the nucleus of the galaxy, the mass ratios will be different. This is also a problem for optical nuclear spectra. Second. in many cases, the amount of extinction toward the nucleus of the galaxy is sufficiently high that the optical and infrared data are in effect sampling different stellar populations. This will also create an inconsistency in the burst mass found.

There is, in general. consistency in the burst ages found, albeit with relatively large uncertainties in our ages in some cases. The ages we find are in agreement with those found by investigators using several different methods. from the analysis of colors of shell structures in IC 51 (McGaugh \& Bothun 1990), to young globular cluster age dating in NGC 4038/9 (Whitmore \& Schweizer 199.5). to EPS analyses similar to our own (e.g. Kurth 1996). The uncertainty on our burst age determination in NGC 520 spans the two different burst ages for the two different nuclei found by Englebracht (1997) and Bernlöhr respectively. The single exception in this sample to this agreement is the burst age in NGC 4194, where the ages found by three different investigators are all inconsistent with one another.

The relatively good agreement in burst ages has two potentially important implications. The first is that, as expected from our testing procedure, the burst age found by our method is relatively insensitive to reddening, even when burst mass is severely affected. The second is that the nuclear and global ages are consistent with one another, suggesting that. in galaxies where the nuclear light does not completely dominate the spectrum, the interaction affects all areas of the
galaxy at roughly the same time, either by shutting off disk star formation or by initiating a starburst. However, this is not necessarily the case in galaxies where the nuclear light dominates the spectrum. NGC 4194. NGC 1222. and Arp 241.

There is also rough agreement in the dynamical ages of the galaxies, and the ages we derive for the starbursts. Although the exact timescales depend on the orbital geometry of the system and the mass ratio of the galaxies, simulations by Barnes \& Hernquist (1996) can give us an idea of when various morphological features appear. In their simulation of the merger of two interacting Milky Way-like galaxies, they found tidal tails began to form shortly ( $\sim 30 \mathrm{Myr}$ ) after the initial morphological disturbance of the galaxies. A bridge between the two galaxies formed at about 100 Myr . the main bodies merged at about 250 Myr. with the nuclei following close behind around 0.5 Gyr. Tidal tails and other morphological features may last 1.5 Gyr or longer. Depending on the bulge-to-disk ratio of the interacting galaxies, star formation may be triggered before the merger of the main bodies. or as this merger occurs (Mihos \& Hernquist 1996). or between approximately $30-300 \mathrm{Myr}$ in the above scenario. We derive a burst age for only one system outside of these constraints. NGC 4676 at 1 Gyr. which has an implied dynamical age of less than about 200 Myr.

### 5.4. Spectral Features

We have put limits on the star formation histories of our merger sample by fitting EPS models to our observed spectra. While this provides good. quantitative information, the uncertainties are too large to make a meaningful comparison between the merger and control samples. To complement the results from from the model fitting described in the previous section, we have measured several spectral
indices for each galaxy, including the equivalent widths of the $\mathrm{H} \alpha+[\mathrm{N} I]$ blend and the $\mathrm{H} \delta$ line, the $41-50$ continuum color defined in K92, and the Rose (1984.1985) indices, Ca II and $\mathrm{H} \delta / \lambda 4045$ as used by Leonardi \& Rose (1996). These are given in Table 5.9. Typical uncertainties in the equivalent widths are about $10 \%$ or 0.4 $\AA$, whichever is greater. Uncertainties in the other quantities are also about $10 \%$. These uncertainties are determined by the scatter in repeated measurements.
$\mathrm{H} \alpha$ equivalent width is plotted against continuum color in Figure 5.24. The mergers and the spiral galaxies fall in nearly the same locus in this diagram. with outliers from both samples, e.g. NGC 1222 and NGC 1569. This would seem to imply that the star formation rates of merger and control samples is nearly the same. The distribution of far-infrared luminosities of the blue merger and control samples is shown in Figure 5.28. The mean value for the control sample is about $3 \times 10^{9} \mathrm{~L}_{6}$, while the blue merger sample is centered around $5 \times 10^{10} \mathrm{~L}_{6}$, more than one order of magnitude higher. indicating a higher level of star formation in the blue merger subsample. Since both $L_{F I R}$ and $\mathrm{H} \alpha$ emission are indicators of current star formation, this result would seem to be in apparent contradiction to that implied by $\mathrm{H} \alpha$. However. the $\mathrm{H} \alpha$ results may, of course. be affected by reddening, and the difference in these two indicators seems to imply that. as with all starbursts, dust does play a role in obscuring starbursts in the merger sample.
$\mathrm{H} \delta$ versus continuum color is plotted in Figure 5.25 . Here we begin to see a separation of the two samples of galaxies. For a given continuum color, the blue merger sample tends to have a stronger $\mathrm{H} \delta$ absorption line. Only about half the merger sample lies in the locus of points defined by the control sample. The three outliers with very blue continuum color but weak $\mathrm{H} \delta$ absorption are Sc or Sd galaxies where the absorption feature is likely to be contaminated by $\mathrm{H} \delta$ emission.

The difference in the two distributions may be understood by making note of the fact that $\mathrm{H} \alpha$ emission is sensitive to the current star formation rate, while $\mathrm{H} \delta$ absorption provides information about the integrated star formation history over the last few hundred Myr. Thus these two graphs may be interpreted to mean that current star formation rates in the two samples are similar. but over the last Gyr. many mergers have had more intense star formation than a morphologically normal spiral.

The Rose indices Ca II and $\mathrm{H} \delta / \lambda 4045$ are plotted in Figure 5.26. Again, there is a clear separation of merger and control samples, with mergers scattering to lower values of the indices indicating stronger Balmer absorption. Most of the outliers in the distribution also are mergers. In Figure 5.27 we have over plotted the indices of the unreddened models we used to fit the galaxy samples. The solid lines are isochrones for pure spiral galaxies with $\tau_{1}=5$ and 15 Gyr and with star formation truncated at times $10^{7}, 10^{8}$, and $10^{9} \mathrm{yr}$, respectively. The dashed lines are evolutionary tracks for spirals with decay times of $\tau_{1}=5$ and 1.5 Gyr and are roughly consistent with those found by Leonardi \& Rose (1996) using their models. The dotted line is the evolution of our assumed star burst. Most of the galaxies, both mergers and spirals lie within the $\tau_{1}=1.5$ track, indicating that their indices are consistent with a spiral galaxy with truncated star formation and no burst. However, depending on the progenitor galaxy type and burst age, most of these galaxies have indices that are also consistent with a starburst in a progenitor population. With so many linear combinations of spiral and burst populations possible, this method cannot be used to break the age-burst strength degeneracy for most of our merger and control samples. Only four galaxies lie to the left of this line and so require a burst, NGC 7252, NGC 4194, NGC 1222, and M 82, although the relative burst ages implied for those galaxies run counter to those expected
from even a casual examination of the spectra, e.g. NGC 1222 and NGC 4194 have older implied ages than NGC 7252.

There are at least two caveats in interpreting these data. First, the Rose indices are unaffected by constant reddening (Leonardi \& Rose 1996). However, when the light contributions from old and young populations are approximately equal, differential reddening between old and young populations begins to affect the indices. This is an important point to consider for our integrated spectra where extinction can vary dramatically over the entire galaxy as seen in Figures 2.3 through 2.5 and in the global to nuclear values of $A_{V}$ from Table 5.5. A second and perhaps more obvious point is that in strongly star forming galaxies, the Balmer absorption features are likely to be contaminated by Balmer emission, again pushing the Rose indices to lower values. This can be a large effect in galaxies with strong $\mathrm{H} \alpha$ emission. For example, using the observed height of the $\mathrm{H} \alpha$ line, heights of $\mathrm{H} \delta$ and $\mathrm{H} \epsilon$ can be calculated used Case B recombination and $A_{V}=1 \mathrm{mag}$. This changes the Ca II index from 0.94 to 0.63 and the $\mathrm{H} \delta / \lambda 404.5$ index from 0.98 to 0.85 , which moves $\mathrm{NGC} 4038 / 9$ to about the location of M 82 in Figures 5.26 and 5.27.

We find a somewhat puzzling relationship between the burst age found by our model fitting procedure and continuum color. This is shown in Figure 5.29. Those galaxies with burst ages longer than about $10^{8} \mathrm{yr}$ have a clear relationship between $t_{2}$ and $41-50$. Those galaxies having younger starbursts tend to have bluer continuum colors, and vice versa. This holds for both the merger and control samples. At ages less than $10^{8} \mathrm{yr}$, however there is no apparent correlation, with some of the galaxies with younger bursts having redder continuum than those with much more evolved bursts. There is no relation between the burst age and
burst mass which could cause this effect (see Figure 5.23), and the distributions of continuum color and burst age are unremarkable. Perhaps coincidently, it is at about this age or slightly younger that the optical depth in our reddened models goes to zero. A plausible scenario is that younger bursts are more strongly reddened, so parameters such as galaxy progenitor type make a larger contribution to the continuum color. This is complicated by that fact that the burst age we find is unaffected by the reddening model we choose. Alternatively, this trend could represent a transition in the dominant spectral feature in the models, for example. as burst luminosity fades sufficiently so that the $4000 \AA$ break and continuum color become more important.

We also note that the model fitting procedure resolves no clear distinction between the merger and control samples. Both are equally well fit by the progenitor plus burst star formation model, and burst sizes and ages found are roughly comparable. A clear difference in the star formation histories as a group is seen, however, in the H $\delta$ absorption feature, representing the last several hundred Myr of star formation, and in the far-infrared luminosity, representing current star formation rates.

Finally, we checked for correlations between $\mathrm{H} \alpha$ equivalent width, the 41-50 continuum color, $\mathrm{H} \delta$ equivalent width, the far infrared luminosity, mass of neutral hydrogen, the upper limit on burst mass from our model fits, and the best fitting burst age. No correlations other than those already discussed were found.

### 5.5. Discussion

### 5.5.1. Star Formation Histories

By fitting EPS models to spectra of merging and control galaxies, we were able to put quantitative limits on the star formation histories of these galaxies, burst age and mass and progenitor type in many cases. The uncertainties in these values tend to be large. However, our data is high-quality, and the assumptions we make about the form of the star formation history, metallicity, IMF, and reddening models are all reasonable ones, and typical of the types of assumptions found in the literature (see references in Chapter 1). The uncertainties we find should therefore also be typical for EPS values based on optical spectra presented in the literature, unless additional constraints are used. This thorough exploration of the uncertainties associated with state-of-the-art EPS model fitting is perhaps the most important result of this thesis.

Because the uncertainties in burst age and mass provided by our fitting method are quite large, we use a more general, but less quantitative, technique to compare the star formation histories of the merger and control samples. We find both the current and recent ( $\lesssim 1 \mathrm{Gyr}$ ) star formation rates in many mergers to be higher than those in galaxies in the morphologically normal control sample, based on far-infrared luminosity and Balmer absorption equivalent widths, respectively. This implies that the gravitational interaction is responsible for triggering star formation in at least some mergers and interacting galaxies.

### 5.5.2. Ongoing Star Formation?

Fitting results on the spiral control sample are similar to those of the blue merger sample. They are well fit by our "two burst" model star formation history even
though we expect a priori, that a single, exponentially declining star "burst" of long duration should fit them well. Although the progenitor types found by the fitting procedure are correlated with the galaxies' morphological types, the best fitting models tend to show recent truncated star formation and several galaxies show evidence for a young star burst, assuming this star formation history. Our fitting procedure does not flag galaxies, by finding large values of $\chi^{2}$, that have star formation histories substantially different from that we assume. This will also be a problem with our merger sample. In spite of good fits by our models, we cannot rule out alternative star formation histories. The model fits on the spiral control sample would seem to imply that in addition to the star formation history inspired by the merger hypothesis of elliptical galaxy formation, other types of star formation, including continuing spiral-like star formation cannot be ruled out.

We find many of the blue mergers are several e-folding times into their star bursts and the have a substantial amount of neutral hydrogen remaining, e.g. NGC 3921 and NGC 7252. Hibbard et al. (1994) showed that for NGC 7252, the remaining neutral hydrogen resided in the galaxy's tidal tails, presumably unavailable for further star formation. This may be the case for many of the mergers. Another possible explanation is that neutral hydrogen remaining in the main body of the merger was not exhausted in a burst of star formation, and is available to feed continuing star formation, as may be the case in NGC 520 (Hibbard \& van Gorkom 1996). To distinguish between these two scenarios. H I mapping of several galaxies in an advanced state of merging is needed.

There is an important consequence to the above arguments. Although our results are consistent with the hypothesis that merging galaxies evolve to form elliptical galaxies, we cannot rule out the possibility that some mergers may evolve
into a more-or-less normal spiral galaxy, based on a stellar populations analysis alone. If this were indeed the case, it is in apparent contradiction to N -body simulations of merging galaxies of approximately equal mass (see e.g. Barnes $\&$ Hernquist 1992, but see Barnes 1996 for mergers between galaxies of unequal mass).

### 5.5.3. IMF

We showed in Chapter 3 that metallicity created little uncertainty in the burst age and mass in blue galaxies, so we need apply no correction except possibly for NGC 3303 and NGC 3656. However, we also showed that choice of IMF did impact the burst mass found in blue mergers, with

$$
f_{b(\text { Scalo })} \approx 2 \times f_{b(\text { Salpeter })}
$$

Our lower limits for the mass in young stars (age <1 Gyr). and even most of our upper ones, are within physical expectations ( $\lesssim 10 \%$ ) for spiral progenitor galaxies. Applying the rough Salpeter to Scalo "correction" above. shows that most of the galaxies have burst masses consistent even with a Scalo IMF. with a few exceptions, e.g. NGC 3448 and NGC 3921. However, as with all mass determinations for this subsample, the results are highly reddening-dependent. A more definitive exploration of this issue must await burst mass estimates which are less sensitive to reddening.

### 5.5.4. Effects of Reddening

We repeat here the main conclusion of Section 3.3.6, that although metallicity, choice of IMF, and star formation history may affect the burst mass found, reddening, by far, is the largest source of uncertainty in determining the mass of a starburst in this method. Very simply, we cannot measure what we cannot see,
and with $A_{V} \gtrsim 10$ for the nuclei of some systems, this light is effectively completely obscured in the optical. The mass found is extremely sensitive to the reddening prescription used in the models. The results from the control galaxies NGC 1832 and M82 stand as a cautionary tale. Using unreddened models for M82 results in a starburst mass that, at $<1 \%$ of the stellar mass, is much too small. On the other hand, using the same reddened models for NGC 1832, where they are not appropriate, results in the unphysically large burst mass of $35 \%$. To get the correct mass from optical data, the reddening must be accounted for correctly, and the appropriate reddening prescription may well be different for each galaxy. For this reason, as emphasized before, we present the range of burst masses as an illustration of the uncertainties involved, and not to make a definitive measurement. Any conclusions drawn from the burst masses we find are, by necessity, tentative ones such as those about the appropriateness of the Salpeter or Scalo IMFs.

Since reddening or differential reddening introduces such large uncertainty in the burst masses. and some other measurements, like $\mathrm{H} \alpha$ equivalent widths. it is also important to emphasize which of our results are unaffected by such effects. Although, burst mass is uncertain, the burst ages appear to be robust. The burst ages returned are unchanged by the choice of reddening model, and are in general consistent with those found by other investigators. Also unaffected is our conclusion that the star formation rates in the blue merger sample are higher than those in the control sample. While $\mathrm{H} \alpha$ measurements are affected by differential reddening, the luminosity of such star formation escapes in the far-infrared where it is observable. Finally, the Rose indices, and H $\delta$ equivalent widths indicated stronger Balmer absorption and therefore stronger star formation in the past Gyr in the blue merger sample than in the control sample. Any extinction in such a post-burst population would tend to weaken the light contribution of that population, and the optical
spectrum would be dominated by the older population. Since the merger sample appears to be more dusty, on average, than the control sample, this effect would weaken the difference between the control sample and merger sample. The fact that we see it even in the presence of reddening indicates it is a strong effect.

### 5.6. Summary and Conclusions

- Spectra of the blue merger sample are quite diverse, with starbursting galaxies, to $\mathrm{E}+\mathrm{A}$, to galaxies with red stellar continuum. Many of the galaxies in this sample contain a substantial amount of dust.
- By fitting EPS models to spectra of merging and control galaxies, we were able to put quantitative limits on the star formation histories of these galaxies. Special emphasis was placed on quantifying the uncertainties in this process, both observational and systematic. This thorough exploration of the uncertainties associated with state-of-the-art EPS model fitting is perhaps the most important result of this thesis.
- Extinction and reddening introduced by the presence of dust contributes the largest single source of uncertainty in determining the mass of a starburst. Burst masses we find are in general extremely sensitive to the reddening prescription used in our models.
- Burst ages appear to be unaffected by reddening as judged by the consistency between reddened and unreddened model fits, and comparison with values found by other investigators, working in both the optical and NIR.
- We find higher current and recent rates of star formation in the merger sample than the control sample based on far-infrared luminosities and

Balmer absorption strengths. respectively. This implies that the interaction is responsible for triggering star formation in at least some merging and interacting galaxies.

- We cannot distinguish between our standard star formation history. based on the merger hypothesis of elliptical galaxy formation. and alternate star formation histories. such as those more appropriate to ongoing spiral-type star formation. based on our model fits alone.
- A Salpeter (1955) IMF appears to be an adequate one to describe star formation in these galaxies. We find no bursts with masses that are unphysical.

Table 5.1. Blue Mergers-Best Fits

| Galaxy | $\chi_{\min }^{2}$ | $\tau_{1}$ | $t_{2}$ | $f_{b}(\%)$ |
| :--- | :---: | :---: | :---: | :---: |
| IC 51 | 1464 | $15 \pm 2.6$ | $7.6 \pm 1.2$ | $0.1 \pm 1.0$ |
| NGC 520 | 2443 | $6 \pm 0.7$ | $7.7 \pm 0.7$ | $0.1 \pm 0.8$ |
| NGC 523 | 1366 | $4 \pm 0.7$ | $8.0 \pm 0.4$ | $0.2 \pm 0.2$ |
| NGC 1222 | 2627 | $7 \pm 2.5$ | $7.3 \pm 0.7$ | $<2.0^{*}$ |
| NGC 1614 | 1194 | $11 \pm 10.9$ | $7.6 \pm 0.6$ | $0.5 \pm 0.8$ |
| NGC 2623 | 2111 | $15 \pm 7.5$ | $8.4 \pm 0.4$ | $2.6 \pm 0.8$ |
| Arp 195 | 1510 | $4 \pm 2^{*}$ | $<8.4^{*}$ | $<1.0^{*}$ |
| NGC 2782 | 1257 | $6 \pm 0.6$ | $7.5 \pm 0.8$ | $0.1 \pm 0.8$ |
| NGC 3303 | 2446 | $3 \pm 37.4$ | $9.0 \pm 1.0$ | $1.4 \pm 1.5$ |
| NGC 3448 | 1242 | $>5^{*}$ | $8.5 \pm 0.1$ | $5.2 \pm 3.0^{*}$ |
| NGC 3656 | 1167 | $3 \pm 0.5$ | $7.1 \pm 1.5$ | $<7.0^{*}$ |
| NGC 3921 | 4275 | $2 \pm 24.9$ | $8.9 \pm 0.1^{*}$ | $15.3 \pm 6.8$ |
| NGC 4038/9 | 3058 | $6 \pm 13.4$ | $<8.6^{*}$ | $0.0 \pm 2.5$ |
| NGC 4194 | 1611 | $15 \pm 10^{*}$ | $8.4 \pm 0.1^{*}$ | $3.2 \pm 2.5^{*}$ |
| NGC 4676 | 6119 | $3 \pm 12^{*}$ | $9.0 \pm 0.3^{*}$ | $<50^{*}$ |
| IC 883 | 2208 | $11 \pm 7.6$ | $8.6 \pm 0.1^{*}$ | $7.5 \pm 0.8$ |
| NGC 5278/9 | 3516 | $1 \pm 44.6$ | $8.9 \pm 0.1$ | $9.5 \pm 8.4$ |
| Arp 241 | 2415 | $10 \pm 6.4$ | $7.5 \pm 0.3$ | $0.1 \pm 1.3$ |
| Arp 220 | 3826 | $5 \pm 0.9$ | $7.5 \pm 0.7$ | $0.1 \pm 0.7$ |
| NGC 6621/2 | 2426 | $6 \pm 11.4$ | $7.6 \pm 6.2$ | $0.1 \pm 10.9$ |
| NGC 7252 | 6068 | $15 \pm 18.0$ | $8.6 \pm 0.1$ | $5.5 \pm 3.8$ |

*Uncertainties or limits derived by eye from contour plot.

Table 5.2. Blue Mergers-Limits

| Galaxy | $<a g \epsilon>$ | Max \% |  | Min \% |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | <1 Gyr | $<0.5 \mathrm{Gyr}$ | <1 Gyr | <0.5 Gyr |
| IC 31 | $5.6{ }_{-0.0}^{+1.1}$ | 7.56 | 4.06 | 4.87 | 2.53 |
| SGC 520 | $6.4_{-0.4}^{+1.8}$ | 5.56 | 2.63 | 1.61 | 1.25 |
| NGC 523 | 7. $0_{-0.3}^{+1.3}$ | 3.23 | 1.46 | 1.13 | 0.50 |
| SGC 1222 | $6.3{ }_{-0.8}^{+2.7}$ | 7.57 | 3.92 | 0.94 | 0.94 |
| NGC 1614 | $5.7-0.7$ | 7.64 | 4.00 | 2.70 | 1.96 |
| NGC 2623 | $5 . i_{-0.1}^{+3.4}$ | 8.61 | 5.14 | 3.38 | 3.17 |
| Arp 19.5 | T. $0_{-0.4}^{+1.3}$ | 3.44 | 1.64 | 1.35 | 0.93 |
| NGC 2782 | $6.4{ }_{-0.4}^{+1.1}$ | 5.49 | 2.58 | 2.15 | 1.42 |
| NGC 3303 | $8.3{ }_{-1.4}^{+1.8}$ | 2.19 | 0.24 | 0.00 | 0.00 |
| NGC 3448 | $5.6{ }_{-0.1}^{+1.7}$ | 12.08 | 8.78 | 7.29 | 5.50 |
| NGC 36.56 | $7.4_{-0.0}^{+0.9}$ | 1.56 | 0.86 | 0.75 | 0.55 |
| NGC 3921 | 7. $6_{-4.6}^{+1.5}$ | 61.87 | 2.17 | 6.23 | 0.35 |
| 入GC 4038/9 | $6.4{ }_{-0.7}^{+2.9}$ | 6.71 | 3.06 | 1.80 | 1.27 |
| 入GC 4194 | $5.6{ }_{-0.0}^{+1.8}$ | 9.53 | 6.10 | 4.89 | 3.99 |
| NGC 4676 | $7.1{ }_{-3.3}^{+2.2}$ | 18.38 | 2.15 | 2.53 | 0.0.3 |
| IC' 883 | $5.5{ }_{-0.0}^{+3.4}$ | 11.65 | 8.34 | 5.22 | 5.21 |
| NGC 5278/9 | 8.9 $9_{-7.8}^{+0.3}$ | 30.92 | 2.75 | 2.54 | 0.0 .5 |
| Arp 241 | $5.9{ }_{-0.3}^{+1.6}$ | 7.23 | 3.64 | 2.96 | 1.86 |
| Arp 220 | $6.6_{-0.6}^{+0.9}$ | 5.60 | 2.68 | 1.83 | 1.07 |
| NGC 6621/2 | $6.4_{-0.6}^{+2.8}$ | 6.25 | 2.80 | 1.58 | 1.33 |
| NGC 7252 | $5.6{ }_{-0.5}^{+3.4}$ | 20.52 | 9.09 | 4.02 | 3.23 |

Table 5.3. Spiral Control Sample-Best Fit

| Galaxy | $\chi_{\text {min }}^{2}$ | $\tau_{1}$ | $t_{2}$ | $f_{b}(\%)$ |
| :---: | :---: | :---: | :---: | :---: |
| NGC 1357 | 2344 | $2 \pm 1^{*}$ | $8.0 \pm 0.7$ | $<0.7{ }^{\text {² }}$ |
| NGC 2705 | 1288 | $2 \pm 1.0$ | $7.8 \pm 0.7$ | $0.0 \pm 1.8$ |
| NGC 3623 | 794 | $1 \pm 4^{*}$ | $9.1 \pm 0.5^{-}$ | $3.9 \pm 3.5$ |
| NGC 3368 | 522 | $2 \pm 0.3$ | $8.1 \pm 0.2$ | $0.1 \pm 0.3$ |
| NGC 1832 | 142.5 | $6 \pm 1.4$ | $7.5 \pm 0.6$ | $0.1 \pm 0.4$ |
| NGC 3147 | 2327 | $4 \pm 10.5$ | <8.7* | <0.4* |
| NGC 3627 | 8:35 | $5 \pm 0.4$ | $\overline{7} .0 \pm 1.0$ | $0.0 \pm 0.5$ |
| NGC 4750 | 1.55 .5 | $4 \pm 1.5$ | $7.6 \pm 0.4$ | $<1.0{ }^{*}$ |
| NGC 5248 | 1618 | $4 \pm 1.6$ | $7.6 \pm 0.8$ | $0.2 \pm 0.1$ |
| NGC 6217 | 2287 | $15 \pm 6.9$ | $<8.5{ }^{*}$ | $2.8 \pm 1.1$ |
| NGC 2276 | 3281 | $15 \pm 17.5$ | $7.7 \pm 0.5$ | $0.7 \pm 1.5$ |
| NGC 2903 | 1238 | $4 \pm 1.8$ | $7.6 \pm 0.5$ | $0.2 \pm 0.2$ |
| NGC 4631 | 3297 | $15 \pm 60.1$ | $8.3 \pm 0.6$ | $6.7 \pm 4.7$ |
| NGC 475 | 3018 | $1.5 \pm 16.2$ | $8.3 \pm 0.1$ | $4.9 \pm 1.2$ |
| NGC 6181 | 1668 | $8 \pm 12.0$ | $7.5 \pm 0.8$ | < $1.5{ }^{*}$ |
| NGC 6643 | 2426 | $14 \pm 7.4$ | < 8.6 ${ }^{\text {- }}$ | $3.7 \pm 1.0$ |
| NGC 1569 | 25.35 | $2 \pm 1.8$ | $7.5 \pm 0.4$ | $0.2 \pm 0.2$ |
| NGC 4449 | 2228 | $1.5 \pm 10.7$ | $8.2 \pm 0.1$ | $5.7 \pm 1.4$ |
| NGC 4485 | 2802 | $1.5 \pm 21.4$ | $8.4 \pm 0.1^{*}$ | $8.7 \pm 5.0^{*}$ |
| NGC 4670 | 2021 | $15 \pm 9.9$ | $8.1 \pm 0.1$ | $2.5 \pm 0.7$ |
| M 82 | 20.57 | $7 \pm 2.3$ | $7.3 \pm 0.7$ | $<1.5^{*}$ |

- Uncertainties or limits derived by eye from contour plot.

Table 5.4. Spiral Control Sample-Limits

| Galaxy | $<a g e>$ | Max \% |  | Min \% |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $<1 \mathrm{Gyr}$ | $<0.5 \mathrm{Gyr}$ | <1 Gyr | $<0.5 \mathrm{Gyr}$ |
| NGC 1357 | $8.2_{-0.7}^{+1.2}$ | 1.38 | 0.68 | 0.15 | 0.15 |
| NGC 2775 | $8.1{ }_{-0.1}^{+1.4}$ | 0.93 | 0.58 | 0.09 | 0.08 |
| NGC 3623 | $9.9{ }_{-2.2}^{+0.1}$ | 2.06 | 0.37 | 0.01 | 0.00 |
| NGC 3368 | S. $2_{-0.1}^{+0.2}$ | 0.61 | 0.40 | 0.44 | 0.20 |
| NGC 1832 | $6.4_{-0.3}^{+1.1}$ | 5.32 | 2.58 | 2.31 | 1.37 |
| NGC 3147 | $6.9{ }_{-0.8}^{+2.4}$ | 4.85 | 2.40 | 1.11 | 0.95 |
| NGC 3627 | 6.6 -0.2 | 4.20 | 2.01 | 2.64 | 1.33 |
| NGC 4750 | $6.9{ }_{-0.0}^{+2.2}$ | 2.60 | 1.33 | 0.87 | 0.65 |
| NGC 5248 | $6.9{ }_{-0.4}^{+2.2}$ | 3.47 | 1.69 | 0.87 | 0.84 |
| NGC 621i | $5.6{ }_{-0.1}^{+2.5}$ | 8.74 | 5.31 | 3.44 | 3.07 |
| NGC 2276 | $5.6{ }_{-0.0}^{+2.5}$ | 8.40 | 4.83 | 2.31 | 2.09 |
| NGC 2903 | $6.9{ }_{-0.3}^{+0.5}$ | 3.56 | 1.77 | 1.70 | 0.93 |
| NGC 4631 | $5.4{ }_{-0.1}^{+3.4}$ | 14.54 | 11.27 | 5.64 | 5.64 |
| NGC 475 | $5.5_{-0.1}^{+3.4}$ | 12.07 | 8.70 | 4.25 | 4.25 |
| NGC 6181 | $6.2{ }_{-0.6}^{+1.3}$ | 7.30 | 3.64 | 2.27 | 1.52 |
| NGC 6643 | $5.7{ }_{-0.1}^{+3.4}$ | 9.69 | 6.30 | 3.95 | 3.05 |
| NGC 1569 | $8.1_{-0.7}^{+1.0}$ | 1.60 | 0.82 | 0.14 | 0.14 |
| NGC 4449 | $5.4{ }_{-0.1}^{+2.5}$ | 13.48 | 10.1.5 | 5.46 | 5.22 |
| NGC 448.5 | $5.3{ }_{-0.0}^{+3.3}$ | 14.79 | 12.69 | 6.18 | 5.98 |
| NGC 4670 | $5.5{ }_{-0.0}^{+1.0}$ | 9.40 | 5.88 | 5.75 | 3.71 |
| M 82 | $6.2_{-0.5}^{+1.3}$ | 6.72 | 3.34 | 2.10 | 1.34 |

Table 5.5. Reddening Values for Selected Mergers

| Galaxy | $A_{V}$ (nuclear) | $A_{V}($ global $)$ | Method | Source |
| :---: | :---: | :---: | :---: | :---: |
| NGC 520 | 11 | 3.7 | $H-K$ | 1 |
|  | 12.3 | ... | $H-K$ | 2 |
| NGC 1614 | 4.8 | 3.4 | $H-K$ | 1 |
|  | 3.3-5.2 | ... | $H-K, \mathrm{~Pa} \beta / \mathrm{Br} \gamma,[\mathrm{Fe} \mathrm{II}]$ | 2 |
|  | 4.9 | $\ldots$ | $J-H, H-K$ | 3 |
|  | 2.3 | $\ldots$ | $\mathrm{H} \alpha / \mathrm{H} \beta, \mathrm{H} \beta / \mathrm{H} \gamma$ | 4 |
| NGC 2623 | 6.6 | 5.4 | $H-K$ | 1 |
|  | 3.8 | ... | $J-H, H-K$ | 3 |
| NGC 2782 | 5.0 | 3.7 | $H-K$ | 1 |
|  | 1.5-4.6 | $\ldots$ | $H-K, \mathrm{~Pa} \beta / \mathrm{Br} \gamma,[\mathrm{Fe} \mathrm{II}]$ | 2 |
| NGC 3303 | 0.5 | 0.0 | $H-K$ | 1 |
|  | 0.1 | $\ldots$ | $\mathrm{H} \alpha / \mathrm{H} \beta, \mathrm{H} \beta / \mathrm{H} \gamma$ | 4 |
| NGC 3656 | 6.1 | 3.8 | $H-K$ | 1 |
| NGC 3921 | 1.4 | 1.1 | $H-K$ | 1 |
| NGC 4194 | 3.0 | 1.6 | $H-K$ | 1 |
|  | 3.5-4.4 | ... | $H-K, \mathrm{~Pa} \beta / \mathrm{Br} \gamma,[\mathrm{Fe} \mathrm{II}]$ | 2 |
|  | 1.1 | $\cdots$ | $\mathrm{H} \alpha / \mathrm{H} \beta, \mathrm{H} \beta / \mathrm{H} \gamma$ | 4 |
| IC 883 | 6.1 | 1.4 | $H-K$ | 1 |
|  | 3.1 | ... | $\mathrm{H} \alpha / \mathrm{H} \beta, \mathrm{H} \beta / \mathrm{H} \gamma$ | 4 |
| Arp 220 | 14 | 10 | $H-K$ | 1 |
|  | 6.4 | $\ldots$ | $J-H, H-K$ | 3 |
| NGC 7252 | 1.9 | 3.7 | $H-K$ | 1 |

Sources: (1) derived from $H-K$ color of Bushouse \& Stanford (1992), assuming $(H-K)_{0}=0.2$, and $E(H-K) / A_{V}=0.063$ (Rieke \& Lebofsky 1985), as in Englebracht (1997), (2) Englebracht (1997), (3) Shier (1995), (4) Liu \& Kennicutt (1995a)

Table 5.6. $A_{V}$ Values Applied to Models

| $A_{V} \propto M_{g a s}$ |  |  |  | $A_{V} \propto M_{\text {gas }} / M_{\text {stars }}$ |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $t_{2}$ | $A_{V}$ | $\tau_{1}$ | $A_{V}$ | $t_{2}$ | $A_{V}$ | $\tau_{1}$ | Av |
| ( $\log \mathrm{yr})$ | (mag) | (Gyr) | (mag) | ( $\log \mathrm{yr}$ ) | (mag) | (Gyr) | (mag) |
| 7.0 | 1.4 | 3 | 0.0 | 7.0 | 8.7 | 3 | 0.0 |
| 7.5 | 1.1 | 5 | 0.2 | 7.5 | 2.5 | 5 | 0.1 |
| 8.0 | 0.6 | 8 | 0.4 | 8.0 | 0.5 | 8 | 0.4 |
| 8.5 | 0.1 | 11 | 0.6 | 8.5 | 0.0 | 11 | 0.6 |
| 9.0 | 0.0 | 14 | 0.7 | 9.0 | 0.0 | 14 | 0.9 |

Table 5.7. Blue Mergers-Burst Mass Dependence on $A_{V}$ Prescription

| Galaxy | $A_{V}=0$ |  |  | $A_{V} \propto M_{g n s}$ |  |  | $A_{V} \propto M_{g a s} / M_{\text {stars }}$ |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Min | Best | Max | Min | Best | Max | Min | Best | Max |
| IC 51 | 0.0 | 0.3 | 1.7 | 1.9 | 3.4 | 6.0 | 1.9 | 5.2 | 5.8 |
| NGC 520 | 0.0 | 0.0 | 1.0 | 0.0 | 0.2 | 2.0 | 0.0 | 0.9 | 14.2 |
| NGC 523 | 0.0 | 0.1 | 1.1 | 0.0 | 0.2 | 10.4 | 0.0 | 0.8 | 10.1 |
| NGC 1222 | 0.1 | 0.4 | 1.5 | 1.1 | 1.8 | 3.2 | 1.1 | 1.6 | 8.5 |
| NGC 1614 | 0.1 | 0.3 | 1.2 | 1.6 | 2.6 | 3.1 | 1.5 | 3.7 | 4.2 |
| NGC 2623 | 0.0 | 2.4 | 3.5 | 2.5 | 3.0 | 4.6 | 2.2 | 2.9 | 4.4 |
| Arp 195 | 0.0 | 0.3 | 1.0 | 0.0 | 1.0 | 1.2 | 0.4 | 22.7 | 28.1 |
| NGC 2782 | 0.0 | 0.0 | 1.3 | 0.0 | 0.9 | 1.6 | 0.5 | 0.7 | 26.6 |
| NGC 3303 | 0.0 | 0.0 | 6.2 | 0.0 | 0.0 | 6.2 | 0.0 | 1.9 | 6.2 |
| NGC 3448 | 4.5 | 4.9 | 4.9 | 4.6 | 5.6 | 7.2 | 4.5 | 5.6 | 7.0 |
| NGC 36.56 | 0.0 | 0.0 | 0.8 | 0.1 | 0.1 | 3.4 | 0.3 | 7.7 | 18.6 |
| NGC 3921 | 6.1 | 14.9 | 58.6 | 6.1 | 13.9 | 92.7 | 6.1 | 13.9 | 100. |
| NGC 4038/9 | 0.0 | 0.0 | 2.1 | 0.0 | 0.0 | 8.1 | 0.0 | 0.0 | 7.8 |
| NGC 4194 | 1.4 | 3.1 | 4.2 | 2.6 | 3.5 | 4.1 | $\underline{.} 2$ | 3.4 | 4.0 |
| NGC 4676 | 0.0 | 17.0 | 53.7 | 1.9 | 17.0 | 100. | 1.9 | 16.3 | 100. |
| IC 883 | 4.2 | 4.4 | 6.2 | 4.4 | 5.1 | 6.6 | 4.4 | 5.1 | 6.4 |
| NGC 527s/9 | 0.0 | 9.5 | 100. | 2.6 | 9.5 | 100. | 2.6 | 9.5 | 100. |
| Arp 241 | 0.0 | 0.1 | 2.1 | 0.9 | 1.7 | 3.1 | 0.8 | 1.6 | 4.5 |
| Arp 220 | 0.0 | 0.0 | 1.3 | 0.0 | 1.1 | 3.8 | 0.5 | 32.1 | 38.5 |
| NGC 6621/2 | 0.0 | 0.0 | 1.7 | 0.0 | 1.4 | 4.3 | 0.0 | 0.0 | 7.3 |
| NGC 7252 | 0.0 | 5.0 | 8.3 | 3.7 | 9.5 | 12.5 | 3.6 | 8.3 | 19.2 |

Table 5.8. Spiral Control Sample-Burst Mass Dependence on $A_{V}$ Prescription

| Galaxy | $A_{v}=0$ |  |  | $A_{V} \propto M_{g a s}$ |  |  | $A_{V} \propto M_{\text {gas }} / M_{\text {stars }}$ |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Min | Best | Max | Min | Best | Max | Min | Best | Max |
| NGC 1357 | 0.0 | 0.1 | 0.7 | 0.0 | 0.3 | 16.7 | 0.1 | 26.9 | 26.9 |
| NGC 2775 | 0.0 | 0.0 | 0.9 | 0.0 | 0.3 | 7.4 | 0.1 | 4.5 | 11.9 |
| NGC 3623 | 0.0 | 3.9 | 6.2 | 0.0 | 3.9 | 6.2 | 0.0 | 3.9 | 6.2 |
| NGC 3368 | 0.0 | 0.1 | 0.3 | 0.0 | 3.1 | 7.1 | 0.0 | 3.1 | 12.0 |
| NGC 1832 | 0.0 | 0.0 | 1.2 | 0.7 | 1.4 | 1.9 | 0.9 | 35.5 | 38.5 |
| NGC 3147 | 0.0 | 0.0 | 2.4 | 0.0 | 1.6 | 2.5 | 0.0 | 1.6 | 7.4 |
| NGC 36.27 | 0.0 | 0.0 | 0.7 | 0.0 | 1.2 | 2.3 | 3.4 | 25.5 | 29.6 |
| NGC 4750 | 0.0 | 0.0 | 0.9 | 0.0 | 0.8 | 2.7 | 0.7 | 26.6 | 26.6 |
| NGC 5248 | 0.0 | 0.1 | 0.9 | 0.1 | 0.8 | 1.6 | 0.3 | 1.5 | 16.9 |
| NGC 6217 | 0.0 | 2.7 | 4.1 | 2.9 | 3.7 | 4.7 | 2.6 | 3.5 | 4.7 |
| NGC 2276 | 0.1 | 0.7 | 2.5 | 2.3 | 3.7 | 4.1 | 2.1 | 3.3 | 3.6 |
| NGC 2903 | 0.1 | 0.2 | 0.6 | 0.5 | 1.4 | 1.5 | 11.2 | 24.4 | 46.2 |
| NGC 4631 | 4.2 | 6.5 | 9.2 | 5.9 | 7.8 | 8.7 | 4.4 | 7.1 | 8.1 |
| NGC 4775 | 2.4 | 4.8 | 6.4 | 4.1 | 6.4 | 6.4 | 3.6 | 5.8 | 5.9 |
| NGC 6181 | 0.1 | 0.3 | 1.4 | 1.0 | 1.2 | 2.3 | 0.9 | 1.3 | 1.7 |
| NGC 6643 | 0.0 | 0.0 | 4.6 | 2.7 | 4.0 | 5.7 | 2.6 | 4.4 | 7.9 |
| NGC 1569 | 0.1 | 0.2 | 0.5 | 0.8 | 0.9 | 1.2 | 5.2 | 9.6 | 13.2 |
| NGC 4449 | 2.9 | 4.1 | 5.7 | 5.9 | 8.6 | 8.9 | 4.4 | 7.2 | 7.9 |
| NGC 4485 | 5.1 | 8.4 | 8.5 | 5.6 | 8.3 | 10.5 | 5.3 | 7. 6 | 10.1 |
| NGC 4670 | 1.0 | 2.6 | 3.5 | 4.3 | 3.4 | 5.4 | 3.8 | 4.6 | 4.8 |
| M 82 | 0.1 | 0.1 | 0.8 | 0.2 | 0.8 | 1.3 | 0.5 | 0.8 | 44.1 |

Table 5.9. Blue Mergers-Line Indices

| Galaxy | $41-50$ | EW(H $\delta)$ | EW (H $\alpha+[\mathrm{N} I I])$ | Ca II | H $\delta / \mathrm{Fe}$ I $\lambda 404.5$ |
| :--- | :---: | :---: | :---: | :---: | :---: |
| IC 51 | 0.39 | -5.2 | 32 | 0.77 | 0.79 |
| NGC 520 | 0.58 | -4.9 | 7 | 0.78 | 0.79 |
| NGC 523 | 0.66 | -2.3 | 21 | 1.00 | 0.84 |
| NGC 1222 | 0.41 | 1.9 | 153 | 1.12 | 0.76 |
| NGC 1614 | 0.41 | -3.0 | 10.5 | 0.82 | 0.81 |
| NGC 2623 | 0.41 | -7.0 | 8 | 0.74 | 0.67 |
| Arp 195 | 0.57 | -2.6 | $\ldots$ | 0.87 | 0.88 |
| NGC 2782 | 0.48 | -2.4 | 51 | 0.83 | 0.87 |
| NGC 3303 | 0.87 | -0.4 | 16 | 1.20 | 0.99 |
| NGC 3448 | 0.22 | -6.7 | .54 | 0.85 | 0.74 |
| NGC 3656 | 0.60 | -3.7 | 10 | 0.78 | 0.84 |
| NGC 3921 | 0.50 | -3.8 | 9 | 0.80 | 0.70 |
| NGC 4038/9 | 0.47 | -0.5 | 63 | 0.94 | 0.98 |
| NGC 4194 | 0.27 | -3.6 | 109 | 0.93 | 0.84 |
| NGC 4676 | 0.63 | -5.3 | 15 | 1.16 | 0.80 |
| IC 883 | 0.37 | -7.2 | 27 | 0.67 | 0.66 |
| NGC 5278/9 | 0.47 | -2.3 | 33 | 0.90 | 0.8 .5 |
| Arp 241 | 0.40 | -2.3 | 48 | 0.95 | 0.88 |
| Arp 220 | 0.51 | -3.3 | 16 | 0.93 | 0.81 |
| NGC 6621/2 | 0.57 | -4.5 | 19 | 0.78 | 0.74 |
| NGC 7252 | 0.35 | -6.4 | 20 | 0.96 | 0.66 |

Table 5.10. Comparison with Previous Results

| Galaxy | Progenitor Type | Burst Age ( $\log \mathrm{yr}$ ) | $\begin{gathered} \hline \text { Burst Mass } \\ (\%) \end{gathered}$ | Source | Notes |
| :---: | :---: | :---: | :---: | :---: | :---: |
| IC 51 | Sc-Sm | $7.6 \pm 1.2$ | 0-6 | 1 | shell colors |
| NGC 520 |  | 8.5-9.3 |  | 2 |  |
|  | Sb | $7.7 \pm 0.7$ | $<14.2$ | 1 |  |
|  |  | 7.1 |  | 3 | nucleus, NIR |
|  |  | 8.3-8.5 | 20-30* | 4 | 2nd nucleus |
| NGC 1614 | $\mathrm{Sa}-\mathrm{Sm}$ | $7.6 \pm 0.6$ | 0.1-4.2 | 1 |  |
|  |  | 7.0 | 23 | 3 | nucleus, VIR |
|  |  | 7.1 | 49 | 5 | nucleus. NIR |
|  | Sc | 7.5 | 5 | 6 | nucleus |
| NGC 2623 | $\mathrm{Sb}-\mathrm{Sm}$ | $8.4 \pm 0.4$ | $<4.6$ | 1 | nucleus. .VIR nucleus |
|  |  | $>7.0$ |  | 5 |  |
|  | $\mathrm{Sb}-\mathrm{Sc}$ | 8.3-8.6 | 4-20 | 6 |  |
| NGC 2782 | Sb | $7.5 \pm 0.8$ | $<26.6$ | 1 | nucleus, NIR |
|  |  | $\sim 7.0$ | 3 | 3 |  |
| NGC 3303 | E-Sm | > 8.0 | $<6.2$ | 1 |  |
|  | Sa | $\cdots$ | 0 | 6 | nucleus |
| NGC 3921 | E-Sm | $8.9 \pm 0.1$ | $>6.1$ | 1 |  |
|  |  | 8.7-9.0 | $\sim 10$ | 7 | UBV colors nucleus |
|  | Sb-Sc | 8.5-9.2 | 2-30 | 6 |  |
| NGC 4038/9 | E-Sm | < 8.6 | $<8.1$ | 1 |  |
|  |  | $\gtrsim 7.0$ | $\ldots$ | 8 | glob. clusters |
| N4194 | $\mathrm{Sb}-\mathrm{Sm}$ | $8.4 \pm 0.1$ | 1.4-4.2 | 1 |  |
|  | $\cdots$ | 7.1 | 12 | 3 | nucleus. NIR nucleus |
|  | Sb | $\sim 8.0$ | 2.3 | 6 |  |
| Arp 220 | Sb | $7.5 \pm 0.7$ | < 38.5 | 1 |  |
|  | S | $\sim 8.0$ | 72 | 5 | nucleus. NIR |
| NGC 6621/2 | E-Sm | < 8.6 | $<7.3$ | 1 |  |
|  | ${ }_{\mathrm{Sa}}^{\mathrm{Sa}}$ | ... | 0 $<19$. | 6 | nucleus |
| NGC 7252 | E-Sm | $8.6 \pm 0.1$ | $<19.2$ | 1 | H I map |
|  | $\ldots$ | 8.0-9.0 | 0.6-12.1 | 10 | UBV colors |
|  | Sc | 8.6-9.1 | 4-3.5 | 6 |  |
|  | Sc | 9.1-9.3 | 20-50 | 11 | nucleus |

"MF dependent
Sources: (1) this paper, (2) McGaugh \& Bothun (1990), (3) Englebracht (1997), (4) Bernlöhr (1993b), (5) Shier (1995), (6) Kurth (1996). (7) Schweizer (1996), (8) Whitmore \& Schweizer (1995), (9) Hibbard et al. (1994), (10) Schweizer \& Seitzer (1992), (11) Fritze-von Alvensleben \& Gerhard (1994).


Figure 5.1 Results for the blue merger sample. Burst age, $t_{2}$, is plotted against progenitor type, $\tau_{1} \cdot \chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\text {min }}^{2}$ is marked with a cross. $\chi^{2}$ is contoured at $(1.05,1.1,1.2,1.5,2,5$, $10,20,50) \chi_{\text {min }}^{2} . f_{b}$ is contoured at $(0.1,0.2,0.5,1,2,5,10,20,50,100)$ percent total stellar mass fraction increasing in all cases from bottom to top of graph.


Figure 5.2 Results for the blue merger sample. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\text {min }}^{2}$ is marked with a cross. Contours are as in Figure 5.1.


Figure 5.3 Results for the blue merger sample. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\min }^{2}$ is marked with a cross. Contours are as in Figure 5.1.


Figure 5.4 Best fitting models and residuals for the blue merger sample. The emission line-cleaned galaxy spectrum is plotted as a series of points, the best fit model is plotted as a solid line, the progenitor populations as a dashed line, the burst population as a dotted line, the continuum contribution as a long-dashed line, and the residual is plotted as a dot-dashed line.


Figure 5.5 Best fit models and residuals for the blue merger sample. Galaxy, model, and residual are plotted as in Figure 5.4.


Figure 5.6 Best fit models and residuals for the blue merger sample. Galaxy, model, and residual are plotted as in Figure 5.4.


Figure 5.7 Results for the spiral control sample. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\min }^{2}$ is marked with a cross. Contours are as in Figure 5.1.


Figure 5.8 Results for the spiral control sample. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\min }^{2}$ is marked with a cross. Contours are as in Figure 5.1.


Figure 5.9 Results for the spiral control sample. $\chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\min }^{2}$ is marked with a cross. Contours are as in Figure 5.1.


Figure 5.10 Best fit models and residuals for the spiral control sample. Galaxy, model, and residual are plotted as in Figure 5.4.


Figure 5.11 Best fit models and residuals for the spiral control sample. Galaxy, model, and residual are plotted as in Figure 5.4.


Figure 5.12 Best fit models and residuals for the spiral control sample. Galaxy, model, and residual are plotted as in Figure 5.4.


Figure 5.13 Age vs. mass for allowed star bursts in the blue merger sample. Dark areas represent regions of acceptable solutions. There is a clear age-mass degeneracy:


Figure 5.14 Age vs. mass for allowed star bursts in the blue merger sample. Dark areas represent regions of acceptable solutions. There is a clear age-mass degeneracy.


Figure 5.15 Age vs. mass for allowed star bursts in the blue merger sample. Dark areas represent regions of acceptable solutions. There is a clear age-mass degeneracy.


Figure 5.16 Age vs. mass for allowed star bursts in the blue merger sample. Dark areas represent regions of acceptable solutions. There is a clear age-mass degeneracy.


Figure 5.17 Age vs. mass for allowed star bursts in the blue merger sample. Dark areas represent regions of acceptable solutions. There is a clear age-mass degeneracy:


Figure 5.18 Age vs. mass for allowed star bursts in the blue merger sample. Dark areas represent regions of acceptable solutions. There is a clear age-mass degeneracy.


Figure 5.19 Results for representative sample of blue galaxies fit with reddened models where $A_{V} \propto M_{g a s} \cdot \chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\text {min }}^{2}$ is marked with a cross. Contours are as in Figure 5.1.


Figure 5.20 Results for representative sample of blue galaxies fit with reddened models where $A_{V} \propto M_{\text {gas }} / M_{\text {stars }} . \quad \chi^{2}$ is contoured with solid lines and $f_{b}$ with dashed lines. The location of $\chi_{\min }^{2}$ is marked with a cross. Contours are as in Figure 5.1.


Figure 5.21 Age vs. mass for allowed star bursts from fitting using models reddened where $A_{V} \propto M_{g a s}$. Dark areas represent regions of acceptable solutions.


Figure 5.22 Age vs. mass for allowed star bursts from fitting using models reddened where $A_{V} \propto M_{g a s} / M_{\text {stars }}$. Dark areas represent regions of acceptable solutions.


Figure 5.23 Upper limit on burst mass plotted against best fitting burst age. Control galaxies are marked with open triangles and blue mergers with filled squares. The solid and dotted lines represent a burst of $5 \%$ mass multiplied by $10^{A_{V} / 2.5}$, where $A_{V}$ is determined from our reddening models.


Figure $5.24 \log \mathrm{EW}(\mathrm{H} \alpha+[\mathrm{N} \mathrm{II}])$ vs. continuum color for both samples of blue galaxies. Control galaxies are marked with open triangles and blue mergers with filled squares.


Figure $5.25 \mathrm{EW}(\mathrm{H} \delta)$ vs. continuum color for both samples of blue galaxies. Control galaxies are marked with open triangles and blue mergers with filled squares. Galaxies with stronger $H \delta$ absorption have $E+A$ type spectra, while those with weaker $\mathrm{H} \delta$ absorption are contaminated by $\mathrm{H} \delta$ emission.


Figure 5.26 Rose Indices Ca II vs. H $\delta / \lambda 404.5$. Control galaxies are marked with open triangles and blue mergers with filled squares. Smaller values for both indices indicate stronger Balmer absorption.


Figure 5.27 Rose Indices Ca II vs. H $\delta / \lambda 4045$. Identical to Figure 5.26 with model index values overlain. The solid lines are isochrones for a pure spiral galaxy with star formation truncated at the time marked. Dashed lines indicate evolution tracks for spiral galaxies with decay constants, $\tau_{1}=5$ and 1.5 Gyr . The dotted line represents the evolution of a pure burst population with $\tau_{2}=10^{8} \mathrm{yr}$. as in our standard models. Smaller values for both indices indicate stronger Balmer absorption.


Figure 5.28 Distribution of $L_{F I R}$ for merger and control samples. The histogram for the total number of galaxies in both samples is drawn with a solid line. The histogram for the blue merger sample only is shaded.


Figure 5.29 Best fitting burst age found through model fitting procedure plotted against the continuum color, 41-50. Control galaxies are marked with open triangles and blue mergers with filled squares. The galaxies separate into two clear groups.

## Chapter 6

## Concluding Remarks

### 6.1. Summary

To examine the stellar populations of interacting or merging galaxies, a sample of 28 objects with disturbed morphology was drawn from the Arp Atlas of Peculiar Galaxies (1966). We obtained integrated spectra of these galaxies. to study their global star formation histories and provide a database for comparison with morphologically disturbed galaxies at high redshift. Quantitative star formation histories were determined by fitting evolutionary population synthesis models to these integrated spectra. Special emphasis was placed on observational and systematic uncertainties, e.g. IMF, metallicity, and reddening. The merger sample was divided into two subsamples for comparison with morphologically normal galaxies. The red subsample consists of galaxies whose spectra resemble those of early-type galaxies, while the blue subsample has moderate to strong $\mathrm{H} \alpha$ emission.

Summarizing our conclusions for the red merger subsample:

- A significant fraction of galaxies in a morphologically selected sample of
mergers and interacting galaxies have integrated spectra resembling those of early-type galaxies.
- The stellar populations implied by the spectra of the red merger sample are indistinguishable from those in a control sample of S 0 galaxies. Small differences in the upper limits on recent star formation between these mergers and a sample of elliptical galaxies may be due to metallicity effects.
- The minimum amount of star formation required in the last 1 Giyr is consistent with zero for all of the red merger and the E/S0 samples.
- The maximum amount of new star formation allowed ranges from 0.2-3.2\% by mass in the merger sample and $0.0-2 . i \%$ in the $\mathrm{E} / \mathrm{S} 0$ control sample. A star burst of $3 \%$ of the stellar mass of an $L^{*}$ galaxy would require that galaxy to pass through a luminous infrared galaxy phase about 1 Gyr ago.

Summarizing our conclusions for the blue merger subsample:

- Spectra of the blue merger sample are quite diverse, with starbursting galaxies, to $E+A$, to galaxies with red stellar continuum. Many of the galaxies in this sample contain a substantial amount of dust.
- By fitting EPS models to spectra of merging and control galaxies, we were able to put quantitative limits on the star formation histories of these galaxies. Special emphasis was placed on quantifying the uncertainties in this process, both observational and systematic. This thorough exploration of the uncertainties associated with state-of-the-art EPS model fitting is perhaps the most important result of this thesis.
- Extinction and reddening introduced by the presence of dust contributes the largest single source of uncertainty in determining the mass of a starburst. Burst masses we find are in general extremely sensitive to the reddening prescription used in our models.
- Burst ages appear to be unaffected by reddening as judged by the consistency between reddened and unreddened model fits, and comparison with values found by other investigators, working in both the optical and NIR.
- We find higher current and recent rates of star formation in the merger sample than the control sample based on far-infrared luminosities and Balmer absorption strengths, respectively. This implies that the interaction is responsible for triggering star formation in at least some merging and interacting galaxies.
- We cannot distinguish between our standard star formation history, based on the merger hypothesis of elliptical galaxy formation, and alternate star formation histories, such as those more appropriate to ongoing spiral-type star formation, based on our model fits alone.
- A Salpeter (195.5) [MF appears to be an adequate one to describe star formation in these galaxies. We find no bursts with masses that are unphysical.


### 6.2. Directions for Future Work

Much more work remains to be done on the stellar populations of merging galaxies before we have a thorough understanding of them. In particular, determining the mass of stars formed in a merger is a difficult problem. Infrared spectra could
be acquired since these data are less affected by reddening. However, one would be need to be careful to match the spatial scale of the population under study, since there may be a significant difference between the nuclear and global stellar populations of a galaxy. Also EPS models that take reddening evolution into account explicitly could be developed or improved to reduce the uncertainty in the reddening and therefore the burst masses found using optical spectra.

The spatial distribution of the star formation can also be explored. Differences in the global and nuclear reddening, thought to be associated with ongoing star formation, hint that starbursts may be occurring primarily in the nuclei of mergers. However, long slit observations and imaging studies could be used to test this assumption explicitly. Also in question is the degree to which the merger will mix the progenitor stellar populations. Can a merger create stellar population gradients or does it destroy them?

Finally, the relationship of the stellar populations in mergers should be compared to other properties of the merger. How do they compare with the kinematics, galaxy environment, or merger age as determined from morphology and/or N-body simulations? Exploration of some of the predictions of numerical simulations, like those of Mihos \& Hernquist (1996) is needed.

Each of these questions is sufficiently broad as to be the topic of a thesis in its own right, but are the next logical steps to understanding the stellar populations in interacting galaxies and mergers.

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