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AN OPTICAL STUDY OF THE NUCLEI
OF S0 STAR-BURST GALAXIES

by

MICHAEL R. JONES

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

MASTER OF SCIENCE

APPROVED, THESIS COMMITTEE:

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HOUSTON, TEXAS

APRIL 1987
AN OPTICAL STUDY OF THE NUCLEI
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by
Michael R. Jones

ABSTRACT
Optical observations of the nuclei of 10 SO Markarian galaxies and two non-Markarian early type galaxies are presented. Spectra from 3500 - 6500 Å with a FWHM resolution of 700 km sec⁻¹ at 5000 Å have been obtained with the McDonald Observatory 2.7m telescope.

The spectra of 7 Markarian galaxies show deep Balmer absorption lines and stellar-like blue continua. The nuclear spectra of UGC 01157, 04902, 06570, and 12618 show strong [O III], [O III], and Hβ emission lines analogous to normal H II regions. None of the galaxy continua appear to have a significant featureless non-thermal component. Nuclear [O III] λ6300 line emission typical of LINER activity is absent. The continua of UGC 02093 and 07933 are remarkably similar to the continua of non-Markarian galaxies UGC 04347 and 06648.

Composite model spectra with IMF exponents of -1, -2.5, and -4 have been constructed from observed stellar spectra. Constant and exponentially decreasing birthrates have been considered. The logarithmic ratio of blended CaH + Hα to CaK absorption line fluxes measured in 5 star-burst galaxies is systematically smaller than the models. The star-burst populations may have ages greater than 5 x 10⁹ years.
Alternatively, the metallicity, IMF, birthrate, or number of star-burst episodes may be different than assumed.
ACKNOWLEDGEMENTS

Many people have contributed in different ways and to various degrees to the realization of this thesis. To my thesis advisor, Dr. Linda Dressel, I express my deepest gratitude. The comments and suggestions offered by Dr. Dressel during numerous and sometimes stormy conversations have been invaluable in the evolution and completion of this work. Her calm, professional demeanor in an often less than congenial atmosphere is truly laudable.

I am indebted to Dr. Reginald Dufour for granting me unlimited, cost free use of the Rice University Picture Processing System. His support and encouragement during the toughest phases of this research is greatly appreciated. I look forward to continuation of our amiable personal and professional relationship. I thank Dr. Jeff Hester for writing software specifically at the request of myself and my advisor on short notice and under heavy pressure.

I would like to thank Drs. Donald Clayton and Charles O'Dell for taking time out of their busy schedules to discuss this project. I especially express my heartfelt thanks to Dr. O'Dell for his words of encouragement and personal intervention at a time when both were so desperately needed.

The observations would not have been possible without the patient assistance of Drs. Ed Barker and Anita Cochran at the University of Texas at Austin. I would like to thank Dr. Barker and the rest of the McDonald Observatory staff
for their gracious hospitality.

I express my deepest affection for and appreciation to the department secretary, Umbe Cantu, for all the little things. Her bright smile, genuine concern, and unselfish willingness to go the extra mile have been a source of inspiration.

I owe everything to my parents and family, particularly my mother. With her loving emotional and financial support during periods of joy and crisis, my mother has provided the foundation upon which my career has been built. I dedicate this thesis and all future work to her with love.

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# TABLE OF CONTENTS

1. INTRODUCTION
   1.1 A Brief Historical Review .......................................................... 1
   1.2 Program Objectives ........................................................................ 6

2. GALAXY OBSERVATIONS
   2.1 Sample Selection ........................................................................... 8
   2.2 The Spectrograph and Detector ...................................................... 8
   2.3 The Observational Procedure ........................................................ 10

3. REDUCTION OF THE DATA
   3.1 Overview of the Reduction Process ................................................. 15
   3.2 Coincidence Correction and Sky Subtraction ................................. 15
   3.3 Data Summation and Quartz Division ............................................ 16
   3.4 Wavelength Calibration ................................................................. 17
   3.5 Correction for Atmospheric Extinction .......................................... 18
   3.6 Flux Calibration ............................................................................ 19
   3.7 Correction for Interstellar Extinction ............................................ 20

4. A GRID OF SYNTHESIZED COMPOSITE SPECTRA
   4.1 Model Calculations ...................................................................... 23
   4.2 Model Results ............................................................................... 28

5. ANALYSIS AND DISCUSSION OF THE GALAXY SPECTRA
   5.1 Nature of the Ionizing Mechanism ............................................... 30
   5.2 Comparison with the Models ........................................................ 32

6. SUMMARY AND RECOMMENDATIONS ................................................ 39

REFERENCES ....................................................................................... 75
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure Captions</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2.1</td>
<td>42</td>
</tr>
<tr>
<td>2.2.2</td>
<td>45</td>
</tr>
<tr>
<td>3.1.1</td>
<td>46</td>
</tr>
<tr>
<td>3.3.1 - 3.3.2</td>
<td>47</td>
</tr>
<tr>
<td>3.4.1</td>
<td>48</td>
</tr>
<tr>
<td>3.6.1</td>
<td>49</td>
</tr>
<tr>
<td>3.7.1 - 3.7.2</td>
<td>50</td>
</tr>
<tr>
<td>3.7.3 - 3.7.4</td>
<td>51</td>
</tr>
<tr>
<td>3.7.5 - 3.7.6</td>
<td>52</td>
</tr>
<tr>
<td>3.7.7 - 3.7.8</td>
<td>53</td>
</tr>
<tr>
<td>3.7.9 - 3.7.10</td>
<td>54</td>
</tr>
<tr>
<td>3.7.11 - 3.7.12</td>
<td>55</td>
</tr>
<tr>
<td>4.2.1</td>
<td>56</td>
</tr>
<tr>
<td>4.2.2</td>
<td>57</td>
</tr>
<tr>
<td>4.2.3</td>
<td>58</td>
</tr>
<tr>
<td>4.2.4</td>
<td>59</td>
</tr>
<tr>
<td>4.2.5</td>
<td>60</td>
</tr>
<tr>
<td>4.2.6</td>
<td>61</td>
</tr>
<tr>
<td>4.2.7</td>
<td>62</td>
</tr>
<tr>
<td>5.3.1</td>
<td>63</td>
</tr>
<tr>
<td>5.3.2</td>
<td>64</td>
</tr>
<tr>
<td>5.3.3</td>
<td>65</td>
</tr>
<tr>
<td>5.3.4</td>
<td>66</td>
</tr>
<tr>
<td>5.3.5</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>68</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table Captions</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.1</td>
<td>69</td>
</tr>
<tr>
<td>2.3.1</td>
<td>70</td>
</tr>
<tr>
<td>3.5.1</td>
<td>71</td>
</tr>
<tr>
<td>3.7.1</td>
<td>72</td>
</tr>
<tr>
<td>3.7.2</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>74</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

1.1 A BRIEF HISTORICAL REVIEW

With his classic 1943 study of galaxies with evidence of unusual nuclear activity, Carl Seyfert laid the foundation for subsequent studies of active galactic nuclei. Seyfert describes this class of galaxies as

"... intermediate-type spirals with ill-defined amorphous arms, their most consistent characteristic being an exceedingly luminous stellar or semistellar nucleus which contains a relatively large percentage of the total light of the system."

Over the following four decades, numerous workers have observationally established that Seyfert galaxies, in general, have complex, asymmetric Balmer line profiles with unusually broad wings and featureless non-stellar blue continua which are immediately obvious in high resolution spectra. The nuclei of Seyfert galaxies are thought to contain compact power-law central energy sources.

Astronomers now recognize several other major categories of unusually active galaxies, each having distinct spectral characteristics and different central energy sources. Quasi-Stellar Objects (QSOs) exhibit highly redshifted spectra that resemble the spectra of Seyfert 1 nuclei to such a degree that Seyfert galaxies are now thought to be low luminosity QSOs. Heckman (1980) has
defined a new class of galaxies dominated by Low Ionization Nuclear Emission-line Regions (LINERs). LINERs are characterized by relatively strong line emission from elements in low ionization states such as [O II], [O I], [N II], and [S II], weak line emission from high ionization states such as [O III], [Ne III], and [He II], modest emission line luminosities, and emission line widths \(~\)comparable to those of the narrow line regions of Seyfert 2 nuclei. Heckman has shown, in the same paper, that LINER spectra can be modelled by shock heating with a wave velocity \(~\)\(\sim\)100 km sec\(^{-1}\). Another energy source, photoionization by a relatively weak non-thermal power-law source, has recently been proposed by Ferland and Netzer (1983) to explain the LINER phenomenon.

First published in 1967, the lists of objects with unusually strong ultraviolet continua and intense line emission compiled by Markarian and his collaborators have proven to be a rich source of newly discovered and rediscovered active galaxies. Referring to their spectroscopic study of 17 Markarian galaxies, Weedman and Khachikian (1969) comment on the diversity of the spectra:

"... detailed analysis of the spectra of the above galaxies makes it quite clear that they do, nevertheless, differ from each other in the degree of excitation of the emission lines, the width of the hydrogen and forbidden
lines, the relative intensities, the density of the continuous spectrum, and the size of the red shift. There are also considerable differences in their outward appearance and morphologic characteristics."

Seyfert galaxies, QSOs, BL Lac objects, and non-Seyfert galaxies have been identified in the Markarian lists. It has been primarily through the study of non-Seyfert Markarians that yet another unique group of objects, star-burst galaxies, showing evidence of vigorous nuclear star formation has been identified.

The continuum characteristics of star-burst galaxies have provided important insight into the physical differences between the central energy sources of star-burst and other types of nuclei. The first qualitative hint of vigorous stellar activity came from the observation by Weedman and Khachikian (1968) of strong Hα λ3970 and higher order Balmer absorption lines in the spectrum of Mrk 2. Weedman (1973) found in his UBV photometric study of Markarian galaxies that non-Seyfert bright nucleus and diffuse Markarian galaxies are segregated from Seyfert galaxies on the two color (U-B) vs. (B-V) diagram. In particular, he found that the non-thermal continua of Seyfert nuclei show a systematic excess in (U-B) compared to the nuclear continua of non-Seyfert Markarian galaxies. Weedman concluded, based on the similarity of the colors of
the bright nucleus galaxies in his survey and the diffuse galaxies found by Sargent (1972) and Weedman (1972) to be analogous to normal H II regions, that the ultraviolet continua of a majority of the bright nucleus Markarian galaxies in his survey arise from hot stars. The UBV photometric study of 196 non-Seyfert Markarian galaxies by Huchra (1977a) showed nearly 75% overlap in the distributions of non-Seyfert Markarian and normal field galaxies. He found, however, that the Markarian galaxies are generally bluer than field galaxies of the same morphological type, implying an unusually high level of recent star formation.

The properties of the emission lines in star-burst, Seyfert, and LINER nuclei differ markedly. Weedman and Khachikian (1968, 1969) found the emission line widths in a number of Markarian galaxies to be narrower than the emission line widths usually measured in Seyfert nuclei. In his spectrophotometry of 23 Markarian galaxies, Weedman (1972) found the widths of the emission lines in Mrk 25 and 52 to be too narrow for these objects to be classified as Seyfert galaxies. Sargent (1972) noted that the range in emission line ratios such as [N III] λ6584: Hα λ6563 and [O III] λ5007: Hβ λ4861 in the sharp emission line galaxies included in his survey of 80 Markarian galaxies is similar to that found in galactic H II regions. Heckman (1980) found a median FWHM emission line width of 480 km sec⁻¹ for the LINER nuclei in his spectrophotometric survey of bright
galactic nuclei and Feldman et al. (1982) found median
[O III] FWHM line widths of 375 km sec\(^{-1}\) and 510 km sec\(^{-1}\)
for Seyfert 1 and Seyfert 2 nuclei, respectively, in a high
resolution study of 116 galactic nuclei. Balzano, however,
has measured a median [O III] FWHM line width of 140 km sec\(^{-1}\)
in her 1983 spectrophotometric survey of 102 star-burst
galactic nuclei. Both Feldman et al. and Balzano found that
the emission line profiles in star-burst nuclei appear to be
Gaussian rather than asymmetric as in Seyfert nuclei.
Balzano also found the [N III] \(\lambda 6584: H\alpha\) and [O III] \(\lambda 5007: H\beta\)
star-burst emission line ratios to be analogous to those
found in galactic H II regions.

Composite evolutionary models have been moderately
successful in explaining the blue colors of star-burst
galaxies. Huchra (1977b) has constructed a grid of models
with a range of initial mass function (IMF) exponents and
exponential birthrates. He duplicated the colors of the
bluest non-Seyfert galaxies in a large sample of field
galaxies and Markarian galaxies from his photometric survey
(1977a), although the results are non-unique. Huchra found
that the colors and H\(\beta\) line emission of the old \((1.2 \times 10^{10}
\) years) models matched the observed data, but only if
enriched in high mass stars relative to the canonical
Salpeter IMF (exponent = 2.35) for the solar neighborhood.
Huchra also found that a high mass enriched IMF is necessary
if internally reddened young models (ages \(\leq 10^{9}\) years) and
composite models with a young burst superimposed on an old
population are to match the observations. Larson and Tinsley (1978) have duplicated the scatter in Arp Atlas (1966) peculiar galaxy colors with a grid of models with monotonically decreasing star formation rates and an approximate solar neighborhood IMF. They found that star-bursts with ages from $2 \times 10^7$ years to $2 \times 10^8$ years superimposed on a red galaxy and involving less than 5% of the total galaxy mass best fit the envelope of the scatter.

1.2 PROGRAM OBJECTIVES

Previous optical studies of star-burst galaxies have concentrated on late type spirals with highly developed disks and irregular galaxies with morphological characteristics that often cannot be conveniently categorized. The Balzano (1983) survey is an exception, but any physical differences that may exist between different morphological types have been blurred by analysing S0, late spiral, and irregular galaxies as a single group rather than seperately. This is the first optical survey devoted solely to S0 lenticular star-burst galaxies. This study is also part of a broader multiband observational investigation of the properties of elliptical and lenticular galaxies that includes radio mapping and infrared measurements with the Infrared Astronomy Satellite.

The nature of the dominate energy source in the nuclei of the star-burst candidates will be qualitatively investigated. Particular emphasis will be placed on confirming the existence of deep Balmer absorption lines, a
large Balmer discontinuity, and strong emission lines in the galaxy spectra. The relative importance of non-thermal energy sources will be assessed.

The galaxies will be compared to a grid of simple composite models using a logarithmic absorption line index [Ca] which is particularly sensitive to A and F spectral type stars. The models will be constructed using observed spectra from the stellar library of Jacoby et al. (1984) and a range of power-law IMFs and birthrates similar to those derived by Miller and Scalo (1979) for the solar neighborhood. This study will attempt to determine whether the solar neighborhood IMF and birthrate can be used to accurately model the young stellar populations in the nuclei of S0 star-burst galaxies.
2. GALAXY OBSERVATIONS

2.1 SAMPLE SELECTION

All of the program galaxies have been selected from the 2380 MHz Arecibo survey of Uppsala General Catalogue (UGC) (Nilson 1973) galaxies by Dressel and Condon (1978). The survey includes all UGC galaxies in the declination range $0^\circ < \delta < +37^\circ$ with apparent photographic magnitudes $m_p \leq +14.0$ inside and $m_p \leq +14.5$ outside the right ascension range $11^h 30^m < \alpha < 13^h 00^m$. 50 star-burst candidates selected for this study satisfy the following criteria: 1) the galaxy is included in the Markarian lists (Markarian et al. 1982 and references therein) of objects with a strong UV excess as determined with a low dispersion objective prism camera; and 2) the Hubble morphological type quoted in the UGC is S0, SB0, S0a, or SB0a. One exception, UGC 05292, is not in the Markarian lists but is known from previous Kitt Peak National Observatory (KPNO) optical observations by O'Connell and Dressel (1978) to have strong Balmer absorption lines. Two other "normal" E and S0 galaxies with spectra thought to be representative of the underlying old stellar population, UGC 04347 and UGC 06648, have also been included. Table 2.1.1 summarizes relevant information on the observed galaxies.

2.2 THE SPECTROGRAPH AND DETECTOR

The nuclei of the galaxies were observed over a period of four days, December 12th–15th 1985, using the University of Texas McDonald Observatory 2.7m Telescope. 2048 channel
spectra were obtained with an Ultraviolet Image Tube Spectrograph (UVITS) and an Intensified Image Dissector Scanner (IIDS) detector similar to the one used at Lick Observatory.

Figure 2.2.1, from the fine book by Eccles, Sim, and Tritton (1983), is a simplified diagram of the Lick Observatory 3-stage IIDS. Electrons ejected from the dissector photocathode are electromagnetically focused on a metal plate with an aperture opening on an electron multiplier. Electrons originating from a specific area of the photocathode will pass through the aperture while all other electrons will hit the plate and be returned to ground. For these observations, a 600 line/mm grating blazed for 4000 Å in first order was used in the UVITS together with a 3-stage intensified red tube chain. The red chain is coupled with UV transmitting fiber optics and employs a Varo 8605/1 "UV" first stage tube with an effective range of 3700 to 8700 Å. Additional information regarding the construction and operation of the UVITS and IIDS can be found in the Appendix of Wills et al. (1985).

Order overlap contamination may be a problem because the spectrograph was used without filters to minimize light loss. Assuming the photocathode response resembles one of the common UV-visible photoemitter response curves shown in Figure 2.2.2, the response of the first stage intensifier tube will be limited by atmospheric cutoff at about 3200 Å. The equation relating angular displacement of the principle
maxima to order $m$, wavelength $\lambda$, and grating spacing $d$ is

$$\theta = \sin^{-1}(m\lambda/d)$$

This relation implies that second order light redward of 3200 Å will overlap first order light redward of 6400 Å, therefore, the galaxy spectra must be considered suspect redward of 6400 Å.

The instrumental resolution in the red and blue regions of the spectrum was estimated by measuring the full width at half-maximum (FWHM) of the 5852.49 Å neon and 4158.59 Å argon comparison lamp lines. The line profiles are Gaussian in shape, the FWHM of the December 12th and December 13th-15th comparison lamp lines ranging from about 11 Å (red) to 10 Å (blue) and 13 Å (red) to 11 Å (blue), respectively. There is no significant difference in the measured resolution of the A and B apertures.

2.3 THE OBSERVATIONAL PROCEDURE

The galaxies, standard stars, and adjacent sky were observed through two apertures, 4'' square on the 12th and 5'' square on the 13th-15th, seperated by 51'' east-west on the sky. An order of magnitude estimate for the linear size of the observed regions of the galaxies can be computed as follows:

$$D = 4''(1\text{ rad}/206265'')(3843\text{ km sec}^{-1})/75\text{ km sec}^{-1}/\text{Mpc}$$

$$= 0.001\text{ Mpc}$$

$$= 1\text{ kpc}$$

where 3843 km sec$^{-1}$ is the mean heliocentric velocity of the galaxies, 75 km sec$^{-1}$/Mpc is the adopted Hubble constant,
and a 4" aperture is assumed. Object and sky were simultaneously observed using a standard computer controlled ABBA aperture switch sequence. Note that comparison of the aperture separation with the dimensions of the galaxies shows that any contamination of the sky observations by galaxy light should be negligible compared to the nuclear light, thus ensuring accurate sky subtraction. The detector counts were accumulated in the computer buffer and written to a 7 track tape after each 50 second integration. The only substantial user interaction involved doing a clunk check before beginning the observation and manual fine adjustment of the tracking rate while guiding on the object. The clunk check deserves further explanation. The images of the spectra on the final image tube phosphor are S shaped curves. The ramp, or position of each curve on the phosphor, is determined at the beginning of the night when the telescope is at zenith by scanning the image of the quartz lamp with the IDS. The image coordinates, used to define the IDS phosphor scan path, are then written to floppy disk. Flexure causes a shift in image position as the telescope is moved away from zenith. The (aptly named!) clunk check compares the position of the shifted image, again using the quartz lamp, to the position of the image at zenith stored on disk and computes a correction factor which is used to redefine the IDS scan path.

Two or three standard stars were observed at the beginning, middle, and end of each night. The procedure for
observing standard stars differed from that for galaxies only in the need to preglow the apertures. The image tube phosphors have a finite rise and decay time ~msec and can retain a significant residual image for up to an hour after prolonged exposure to a bright source. Calibration uncertainties due to this delayed phosphor response were minimized by preglowing, or briefly exposing each aperture to the standard star just before initiating the ABBA observing sequence. The residual image was monitored after completion of the observation, typically decaying to an acceptable level in 15 to 30 minutes. Seeing was estimated during each standard star observation by comparing the stellar image to the aperture image on the video monitor. Seeing generally improved from about 10" at the beginning to about 6" at the end of each night, an effect probably caused by air cells inside the closed telescope tube which eventually dissipate as the telescope cools to the ambient air temperature outside the dome. Atmospheric losses and image degradation due to seeing were ameliorated by observing both the galaxies and standard stars near transit, which occurs when the local sidereal time (LST) equals the right ascension of the object.

The galaxy spectra, calibrated with a standard star derived instrumental response curve, will be systematically in error because of the poor seeing conditions. The spectrograph aperture was smaller than the seeing disk, therefore, only a fraction of the standard star image was
observed and too few counts channel\(^{-1}\) sec\(^{-1}\) were detected. As a result, the instrument, judged from the response curve, will appear to be less sensitive than it actually is. The refractive index of air increases with decreasing wavelength, resulting in a larger blue than red seeing disk. For this reason, the systematic error will be more serious in the blue than the red end of the response curve. Some of the S0 galaxies contain H II regions which are probably dispersed throughout the nuclei. Only parts of those H II regions that happen to be near the edge of the aperture will be observed. Non-Seyfert Markarian galaxy continuum colors also generally redden with increasing aperture size, so the observed nuclear spectrum may be contaminated by light originating from points in the galaxy image outside the aperture that is redder than the nuclear continuum.

Spectra of neon, argon, and quartz halide lamps were taken at the beginning and end of each night with the telescope stowed in the zenith position. The neon and argon emission line spectra were used later in the reduction process to compute the spectrograph dispersion curve. Assumed to have a smooth continuum, the quartz spectrum was used to derive the relative sensitivity of each channel. Only the lamp spectra taken at the end of the night were used to reduce the galaxy spectra since nearly all of the galaxy observations were performed after local midnight.

We observed most galaxies long enough to accumulate at least 10,000 counts in the region where the system
sensitivity peaks, about 5000 Å in this case. The goal here was to achieve an acceptable signal-to-noise ratio (S/N) for the greatest possible number of galaxies. A √n photon statistical error of 1% was not actually realized because the instrument has an average multiplex factor of 2 counts/photon, a characteristic we were unaware of at the time the observations were made. The standard stars, of course, appear much brighter and the S/N of the spectra typically exceeds 100 even after division by the multiplex factor. Noise in the quartz lamp spectrum, which must have a high S/N if differences in channel sensitivity are to be cleanly delineated, was minimized by adjusting the illumination such that the number of counts accumulated during each integration nearly equaled the capacity of the computer buffer. Table 2.3.1 shows √n signal-to-noise ratios for the summed raw December 12th spectra of galaxy UGC 12618, standard star Feige 110, and the end of the night quartz lamp. These spectra, which have been coincidence corrected and divided by the multiplex factor, are representative of the data in general.
3. REDUCTION OF THE DATA

3.1 OVERVIEW OF THE REDUCTION PROCESS

The raw spectra were reduced with the Rice University Picture Processing System (RUPPS) from a Flexible Image Transport System (FITS) format data tape provided by the University of Texas at Austin. The individual steps involved in the data reduction process and the order in which the steps were taken is indicated in Figure 3.1.1. Each step is described in greater detail in the subsections that follow.

3.2 COINCIDENCE CORRECTION AND SKY SUBTRACTION

The object and sky files were coincidence corrected using the standard instrumental deadtime, 0.63 msec, taken directly from the DIVCAL software used for IIDS data reduction at the University of Texas at Austin. RUPPS and DIVCAL utilize the same coincidence correction algorithm \( R = -\ln(1-rT)/T \), where \( R \) is the true count rate, \( r \) is the apparent count rate, and \( T \) is the instrumental deadtime.

Each ABBA sequence of object data was sky subtracted according to the following pattern:

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<td>t4</td>
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A and B designate the apertures, O and S designate object and sky observations, respectively, and the rectangles show the pairs used for sky subtraction.
3.3 DATA SUMMATION AND QUARTZ DIVISION

The sky subtracted data was summed and divided by a normalized quartz lamp spectrum to correct for sensitivity differences between channels. Using notes in the observing log book as a guide, poor quality data was identified and discarded before summation. One observational problem in particular, an intermittent camera focus problem on the 15th, resulted in a lower than normal count rate and broadened emission lines. The affected data was identified by visual inspection and excluded from the summed data.

The RUPPS QNORML routine was used to fit the quartz lamp spectrum with a series of Legendre polynomials. The series is of the form

\[ q(c) = A_0 + A_1 \times P_1(c) + A_2 \times P_2(c) + \ldots + A_n \times P_n(c) \]

where \( c \) is the channel number and \( n \), the maximum Legendre polynomial order, is set by the user. Division of the spectrum by the fit produces a map of relative sensitivity versus channel. Unfortunately, numerical problems often resulted in a fit that oscillated severely over the first 500 or so channels of the spectrum. The oscillations were nearly eliminated by splitting the spectrum roughly in half, fitting the first 1124 and last 1125 channels separately. A 2048 channel normalized spectrum was formed by joining the halves at a channel lying close to the midpoint of the 201 channel wide region of overlap. Although splitting the spectrum was time consuming, the benefits derived can best be appreciated by examining Figures 3.3.1 and 3.3.2. Figure
3.3.1 is the result of fitting a 21st order Legendre series to the entire December 14th A aperture quartz spectrum whereas Figure 3.3.2 is the result of seperately fitting each half of the same spectrum with a 21st order Legendre series. Ignoring the noise due to poor photon statistics, the improvement in the fit is obvious.

3.4 WAVELENGTH CALIBRATION

A dispersion solution was derived for each aperture using the RUPPS WLFIT routine. The neon and argon comparison lamps were used for the red and blue regions, respectively, of the data. The channel number corresponding to the center of each emission line to be used in the fit is determined by the routine after the wings of the line are manually marked by the user. The routine then uses a least-squares algorithm to fit corresponding wavelength-channel number pairs with a polynomial of the form

\[ \text{wl}(c) = A_0 + A_1 \times c + A_2 \times c^2 + \ldots + A_n \times c^n \]

where \( c \) is the channel number corresponding to the center of the emission line of wavelength \( \text{wl}(c) \), and \( n \) is the user specified polynomial order. The user is allowed to modify the weight of each point to produce the best fit. The \( A_0 \) and \( A_1 \) coefficients are actually written to the headers of the data files and used by the RUPPS graphics routines to display the data.

A 7th order polynomial fit of 27 emission lines extending from the 3502.471 Å argon line to the 6402.25 Å neon line was found to be satisfactory. The \( \chi^2 \) deviation of
the discrete points from the fit was between 3.0 and 3.5 Å
for all of the data. Figure 3.4.1, a plot of the December
15th A aperture residuals, is typical.

3.5 CORRECTION FOR ATMOSPHERIC EXTINCTION

The wavelength calibrated data were corrected for
atmospheric extinction according to the standard formula

\[ \log_{10} \left( \frac{F'(\lambda)}{F(\lambda)} \right) = k(\lambda)X/2.5 \]

where \( F(\lambda) \) is the flux incident on the telescope, \( k(\lambda) \) is
the wavelength dependent extinction coefficient, and \( X \) is
the air mass.

Ideally, the extinction coefficients should be measured
by observing one or more standard stars at several values of
\( X \). The slope of a plot of magnitude at wavelength \( \lambda \) (or,
more likely, magnitude through a filter where \( \lambda \) is some
predominate wavelength over the filter bandpass) versus \( X \)
would yield \( k(\lambda) \). The standard McDonald Observatory
extinction coefficients, measured by Hiltner (1956) and used
in DIVCAL, had to suffice as too few standard star
observations were made to independently derive \( k(\lambda) \) using
the preceding method. The standard extinction coefficients
are reproduced in Table 3.5.1 for reference. RUPPS
interpolates by fitting a cubic spline to the discrete
points.

The air mass calculations were based on the usual sec z
plane-parallel atmosphere assumption, where \( z \) is the angular
zenith distance. In practice, an average value of sec \( z \) for
each observation was computed from the local hour angle
(LHA) and δ of the 50 second integration closest in time to the middle of the observation. For example, the LHA and δ for the second A aperture integration of an observation comprised of two ABBA sequences would be used to calculate sec z. Finally, the calculations included the correction to sec z cited in Astronomical Techniques (1962). The correction reads as follows:

\[ X = \sec z - 0.0018167(\sec z - 1) - 0.002875(\sec z - 1)^2 - 0.0008083(\sec z - 1)^3 \]

where sec z = 1/(sin φ sin δ + cos φ cos δ cos LHA), and φ is the latitude of the observatory. The correction terms turned out to be negligible compared to other uncertainties, amounting to no more than 0.33% of sec z in the worst case, the December 15th observation of UGC 01157 at an air mass of about 2. The air mass for the majority of the observations was between 1 and 1.2.

3.6 FLUX CALIBRATION

The instrumental response curve was computed using the RUPPS CALSPLINE routine and fluxes from the Kitt Peak National Observatory (KPNO) IIDS standard star list. Each set of KPNO standard star data consists of 29 well known fluxes, specified in magnitudes per unit frequency interval, which extend from 3200 Å to 8370 Å. Each flux represents the average stellar flux over a bandwidth of 50 Å for center wavelengths < 5200 Å and 100 Å for center wavelengths > 5200 Å. CALSPLINE computes the calibration points by summing the observed spectrum counts over the same bandpasses,
normalizing the sums by the number of channels in the bandpass and the integration time, and dividing the normalized sums by the corresponding standard fluxes. The response curve is generated by fitting a cubic spline to the logarithm of the discrete points, each point being the average of the calibration points for all of the stars used in the fit weighted according to the integration time of each observation. The user has the option of applying a correction to spectra observed through "grey" clouds. The "grey" correction was not necessary for this data since the weather was generally clear during the observing run. Figure 3.6.1 is a typical response curve.

The galaxy spectra were flux calibrated using the RUPPS CALIBRATE routine. CALIBRATE divides the spectrum by the appropriate instrumental response curve. After division by the response curve, the spectrum is normalized by the integration time to yield flux units of ergs cm$^{-2}$ Å$^{-1}$ sec$^{-1}$.

3.7 CORRECTION FOR INTERSTELLAR EXTINCTION

A simple program was written to correct for interstellar extinction according to the relation

$$\log_{10} \left( \frac{F'(\lambda)}{F(\lambda)} \right) = \left\{ \frac{A(\lambda)}{E(B-V)} \right\} E(B-V) / 2.5$$

where $F(\lambda)$ is the flux incident on the atmosphere, $A(\lambda)/E(B-V)$ is the extinction in magnitudes at wavelength $\lambda$ normalized by color excess, and $E(B-V)$ is the color excess in the direction of the galaxy. Two average extinction curves were considered, that determined by Savage and Mathis (1979) and by Seaton (1979). The small difference in the
R = A(V)/E(B-V) normalization of these curves, 3.1 for Savage and Mathis versus 3.20 for Seaton, was not considered as important as the numerical accuracy with which the curves could be fit by the program. The program interpolates between discrete points with a cubic spline, the accuracy of the fit obviously improving as the number of points included in the fit increases. The Seaton curve was finally selected because it has more than four times as many points in the 3500 to 6500 Å optical region as the curve of Savage and Mathis. Both curves are compared in Table 3.7.1.

E(B-V) reddening estimates for all but one galaxy were computed from the blue extinctions, A(B) = 4 x E(B-V), published by Burstein and Heiles (1984). This paper includes reddening estimates for nearly 13,000 UGC galaxies, some of which, the authors point out, may be in error due to data handling problems. The published values, based on the correlation between galactic HI column density, galaxy counts, and known reddening of galactic globular clusters and RR Lyrae stars outlined in Burstein and Heiles (1978), were confirmed using equation (4) from the same paper

\[ E(B-V) = -0.0372 + 0.357 \times 10^{-3} N_H - 0.346 \times 10^{-4} R N_H \]

where \( N_H \) is the galactic HI column density in the direction of the object from the 21 cm survey of Heiles (1975) and R is the residual in galaxy counts taken from Heiles (1976). Specifically, R is the residual of a least-squares fit to the observed galaxy counts described in the 1976 paper and is interpreted by Burstein and Heiles as an indicator of the
variability in the galactic gas-to-dust ratio. A sample calculation for UGC 02093 goes as follows:

\[ N_H = 325 \text{ contour units from Heiles (1975)} \]
\[ R = 1.5 \text{ contour units from Heiles (1976)} \]

\[ E(B-V) = -0.0372 + (0.357 \times 10^{-3})(325) - (0.346 \times 10^{-4})(1.5)(325) \]

\[ = 0.06 \]

Differences between the published and derived values could be ascribed in nearly all cases to errors in interpolation of the contour maps by eye. Calculated reddening values are compared against published reddening values in Table 3.7.2. The agreement is reasonably good for all but two galaxies, UGC 03265 and UGC 06570. The reddening of UGC 06570 is negligible in either case; the published value was adopted. The adopted reddening of UGC 03265, \( E(B-V) = 0.120 \), is the average of seven UGC galaxies within 2° galactic latitude and 3° galactic longitude of UGC 03265 with published reddening values that could be reproduced. Figures 3.7.1 through 3.7.12 are the final spectra corrected for Doppler shift.
4. **A Grid of Synthesized Composite Spectra**

4.1 **Model Calculations**

Stellar populations were synthesized for three
different power law Initial Mass Functions (IMF) and two
different relative birthrates (b(t)). IMF exponents of -4,
-2.5, and -1 were chosen to bracket the range of values
adopted in Miller and Scalo (1979) for the solar
neighborhood. Constant and exponentially decreasing
relative birthrates, properly normalized according to the
physical constraint

$$\int_0^{T_s} b(t)dt = T_s$$

where $T_s$ is the elapsed time after the beginning of star
formation, were used. The exponential time constant, $\tau$, is
shown by Miller and Scalo (1979) to be a rather slowly
varying function of the assumed age of the galaxy and is
numerically of the order of $10^9$ years. A representative
value of $5 \times 10^9$ years was chosen for the models.

The Present Day Mass Function (PDMF) is related to the
IMF as follows:

$$PDMF = T_s^{-1} \int_{T_m}^{T_s} b(t)dt, \quad T_m < T_s$$

$$= IMF, \quad T_m > T_s$$

where $T_m(M)$ is the main-sequence lifetime of a star of mass
M. The number of stars in the mass range $M_1 < M < M_2$ (solar
units) observed on the main-sequence at time $T_s$ is
\[ N(M_1 \leq M \leq M_2) = \int_{M_1}^{M_2} \text{PDMF} dM = T_s^{-1} \int_{M_1}^{M_2} \text{IMF} \int_{T_s}^{T_m} b(t) dt dM, \quad T_m < T_s \]

\[ = \int_{M_1}^{M_2} \text{IMF} dM, \quad T_m > T_s \]

The main-sequence lifetime can be approximated by \( T_m(M) = M^{-2.2} \times 10^{10} \) years assuming solar abundance. \( N \) can be evaluated analytically for a constant relative birthrate, but must be approximated for \( b(t) \propto \exp(-t/\tau) \) by a polynomial expansion when \( T_m < T_s \):

\[
N(M_1 \leq M \leq M_2) \propto T_s^{-1} \int_{M_1}^{M_2} \int_{T_s}^{T_m} \left[ (T/\tau) \exp(-t/\tau) \right] / \left[ 1 - \exp(-T_s/\tau) \right] dt dM
\]

\[ = \left[ 1 - \exp(T_s/\tau) \right]^{-1} \int_{M_1}^{M_2} \left[ 1 - \exp(10^{10} M^{-2.2}/\tau) \right] M^n dM \]

\[ = \left[ 1 - \exp(T_s/\tau) \right]^{-1} \left\{ [M^{-2.2}/1.1 + M^{-4.4}/2.2 + 2M^{-6.6}/9.9] \right\}_M^{M_2}, \quad n=1 \]

\[ = \left[ 1 - \exp(T_s/\tau) \right]^{-1} \left\{ 2/((n+1.2)M^{n+1.2}) + 2/((n+3.4)M^{n+3.4}) \right\} \]

\[ + [4/3]/((n+5.6)M^{n+5.6}) \right\}_M^{M_2}, \quad n > 1 \]

Only the first two terms in the preceding expansions needed to be retained; the ratio of the third term to the sum of the first two terms never exceeded 6%. In practice, \( N \) was computed for at least ten mass intervals extending over the range 0.1 \( M_\odot \) to 40 \( M_\odot \).

The pre-main-sequence evolutionary history of the stars has been ignored in the models. Pre-main-sequence evolutionary tracks of Ezer and Cameron (1967) show that stars with masses greater than about 5 \( M_\odot \) descend the
Hayashi track and settle on the main-sequence in times of the order of $10^6$ years or less after initiation of protostellar collapse. Stars with masses less than $5 \, M_\odot$ cease to be fully convective and begin to develop radiative cores in about the same time, $10^6$ years. At this stage, the effective temperatures and luminosities of these stars approach zero-age main-sequence (ZAMS) values. The preceding considerations suggest that pre-main-sequence evolutionary effects really are of minor importance since $10^6$ years is negligible compared to the main-sequence lifetimes of all but the most massive stars.

The post-main-sequence status of stars beyond the main-sequence turnoff point has been included in the models. The Hertzsprung-Russell (HR) diagrams of older Galactic star clusters have well developed giant and subgiant branches; the theoretically computed timescales for post-main-sequence evolution of low mass stars are long enough such that the probability of actually observing these stars in the subgiant or giant phase becomes non-negligible. The total number of stars in a particular mass interval that have turned off the main-sequence in time interval $T_S$ is the difference between the total number of stars ever formed and $N(M_1 \leq M \leq M_2, t=T_S)$:

$$N_{PM}(M_1 \leq M \leq M_2, t=T_S) = \int_{M_1}^{M_2} \text{IMF} dM - N(M_1 \leq M \leq M_2, t=T_S)$$

In the models, the probability that post-main-sequence stars will be observed in the red giant phase has been approximated by the relation
\[ P(M_1 \leq M \leq M_2, t=T_s) = \frac{T_r - T_m}{T_s - T_m} \]

where \( T_r \) is the time of initiation of thick helium shell burning or helium core ignition in intermediate and low mass stars and carbon core ignition in high mass stars. Finally, the number of stars observed in the red giant phase is

\[ N_r(M_1 \leq M \leq M_2, t=T_s) = P(M_1 \leq M \leq M_2, t=T_s)N_{pm}(M_1 \leq M \leq M_2, t=T_s) \]

In this approximation, after helium or carbon core ignition occurs the stars are assumed to produce remnants such as neutron stars, black holes, or faint white dwarfs on timescales that are so short that the \((1-P)N_{pm}\) stars not assumed to be in the red giant phase can be neglected.

Support for this approximation comes from the evolutionary calculations of Weaver et al. (1978) where it is shown that the timescale for carbon core burning in stars with masses \( \geq 15 M_\odot \) is very rapid, of the order of \( 10^3 \) years or less. \( T_r \) and accurate values for \( T_m \) (when the core hydrogen abundance, \( X_c \), drops to zero) have been taken from the high mass models of Brunish and Truran (1982), intermediate mass models of Becker (1981), and the 2.2 \( M_\odot \) model of Mengel et al. (1979) and Sweigart and Gross (1978). The stars are assumed, for simplicity, to evolve without mass loss despite mounting observational evidence for strong stellar winds and appreciable mass loss in massive stars. Determination of typical mass loss rates is currently an area of active research, therefore, evolutionary calculations which include mass loss such as those of Brunish and Truran (1982) must still be considered speculative.
An equivalent Morgan-Keenan (MK) spectral class was assigned to each main-sequence (luminosity class V) mass interval using the empirical correlation of mass with MK spectral class cited in Allen (1973) and Mihalas and Binney (1981) (for comparison). For the purpose of assigning an equivalent spectral class, each mass interval was represented by the average mass \( \langle M \rangle = 0.5(M_1+M_2) \). The empirical correlation of effective surface temperature, \( T_e \), and bolometric correction, B.C., with spectral class of Humphreys (1978), Bohm-Vitense (1981), and Mihalas and Binney (1981) was used to assign an equivalent spectral class to the red giant stars. \( T_e \) comes directly from the stellar models. The equivalent luminosity class was deduced by comparison of the absolute visual magnitude, \( M_V \), computed from the B.C. and the luminosity of the stellar model to the empirical correlation of \( M_V \) with combined spectral-luminosity class of Allen (1973), Corbally and Garrison (1984), and Mihalas and Binney (1981).

Each model spectrum is the sum of individual moderate resolution (~4 Å FWHM) stellar spectra selected from the magnetic tape library of 161 stars compiled by Jacoby et al. (1984). All but two of the library stars are solar metallicity; only solar metallicity stars without emission lines were used in the models. For each mass interval, a library star with a spectral-luminosity class closely matching that assigned to the interval was selected and weighted by \( N \) if the star lies on the main-sequence or by \( N_r \).
if the star is a red giant. In addition, the spectra were corrected to a common distance of 10 pc using the dereddened V magnitudes listed for each star in the library and the corresponding typical $M_V$ determined from the empirical correlation of $M_V$ with spectral-luminosity class.

4.2 MODEL RESULTS

Models with ages of $0, 10^7, 10^8, 10^9$, and $5 \times 10^9$ years were constructed. A sample sequence of spectra with a $-2.5$ IMF and constant birthrate is shown in Figures 4.2.1 through 4.2.5. Stars of decreasing mass evolve off the main-sequence as the population ages, resulting in deepening of the Balmer absorption lines and development of the pronounced Balmer discontinuity seen in the composite spectra.

Figure 4.2.6 compares the $10^8$ and $10^9$ year models with constant birthrate to the $2 \times 10^8$ and $1.2 \times 10^9$ year models with nearly constant birthrate of Huchra (1977b). The unreddened model $(B-V)$ was synthesized using the filter response curves and zero points of Allen (1973):

$$(B-V) = 2.5 \log_{10} \left( \frac{F(V)}{F(B)} \right) + 0.77$$

$F(V)$ and $F(B)$ are the spectrum fluxes convolved with the $V$ and $B$ response curves. Both sets of models reddened by at least 0.07 magnitudes in $(B-V)$ with increasing age. The models agree to within about 0.2 magnitudes in $(B-V)$, although the high mass enriched Huchra models are systematically redder.

Figure 4.2.7 compares the $5 \times 10^9$ year constant and
exponential birthrate models to the $1.2 \times 10^{10}$ year constant and exponential birthrate models of Huchra (1977b). The exponential birthrate models are redder than the constant birthrate models, the magnitude of the reddening being smaller in the models with depressed high mass IMFs (large negative exponents). The models are systematically bluer in (B-V), an effect probably caused, in part, by the difference in ages. The epoch from $5 \times 10^9$ years to $1.2 \times 10^{10}$ years spans a crucial stage in the evolution of the stellar population when stars with masses of the order of a solar mass reach main-sequence turnoff. That main-sequence turnoff of solar mass stars has a dramatic effect on the integrated light of the stellar population follows not only from the fact that the number of solar mass stars generally far exceeds the number of high mass stars (depending on the IMF exponent), but also from stellar evolution models which show that the luminosity of a solar mass star increases by 2 to 3 orders of magnitude as it ascends the red giant branch (compared to the luminosity of a high mass star, which remains nearly constant). It is unlikely that the contribution to the continuum flux by interstellar gas, neglected in the models but included in the calculations of Huchra, is significant. Huchra finds that the gas contributes 20% or less to the V band flux of his models with ages of $2 \times 10^8$ years or older and that the color of the gas is similar to the color of the stellar continuum.
5. **ANALYSIS AND DISCUSSION OF THE GALAXY DATA**

5.1 **NATURE OF THE IONIZING MECHANISM**

Various qualitative lines of evidence indicate the presence of hot, young stars in the nuclei of these S0 galaxies. Compared to normal galaxies UGC 04347 and 06648, the spectra of the star-burst candidates are elevated in the blue end, one of the characteristics that originally led to the inclusion of the galaxies in the Markarian lists. Close examination of the blue end of the spectra reveals that most have deep Balmer absorption lines, Hα λ4101, Hγ λ3889, and Hη λ3835 in particular, and a pronounced Balmer discontinuity blueward of 3648 Å. The Balmer lines in the spectra of dwarf stars in the stellar library diminish in strength in spectral types later than early F because there are relatively few hydrogen atoms in the excited n=2 state at effective surface temperatures \( \sim 7000 \) K and lower. Furthermore, the Balmer lines diminish in strength and the Balmer discontinuity disappears in spectral types earlier than late B because the hydrogen atoms are mostly ionized at effective surface temperatures \( \sim 12000 \) K and higher, therefore, the deep Balmer lines and pronounced Balmer discontinuity in the spectra of the star-burst candidates indicate the presence of A stars with main-sequence lifetimes \( \sim 10^9 \) years.

The presence of strong [O III] \( \lambda\lambda3726, 3729, [O III] \( \lambda\lambda4959, 5007, \) and Hβ emission lines in the nuclei of UGC 01157, 04902, 06570, and 12618 suggest the existence of
complexes of H II regions photoionized by OB associations. The absence of \( [\text{O I}] \, \lambda 6300 \) line emission in the spectrum of any galaxy in the survey violates the arbitrary but well accepted Heckman (1980) LINER criterion that \( [\text{O I}] \, \lambda 6300 \) emission be at least one third as intense as \([\text{O III}] \, \lambda 5007 \) emission. It seems reasonable to conclude, therefore, that LINER activity is not the dominate ionization mechanism at work in the nuclei of the galaxies.

Seyfert activity can probably be discounted as the dominate ionizing source because none of the galaxy spectra show the kind of featureless power-law continuum typical of Seyfert nuclei, although an ultraviolet power-law continuum obviously cannot be ruled out based on the optical spectra. Recall that Seyfert 1 nuclei have distinctive asymmetric Balmer line profiles with broad wings \( \sim 1000 \text{ km sec}^{-1} \) wide. Recall also that Feldman et al. (1982) found median \([\text{O III}] \, \text{FWHM} \) line widths of 375 km sec\(^{-1}\) and 510 km sec\(^{-1}\) for Seyfert 1 and Seyfert 2 nuclei, respectively, whereas Balzano (1983) found a median of 140 km sec\(^{-1}\) for her star-burst galaxies. Unfortunately, the instrumental resolution, roughly 700 km sec\(^{-1}\) at 5000 Å, was not high enough to discern either the nature of the line profiles or the widths; the unresolved line profiles are very similar to the instrumental profile.

The nuclei of UGC 02093 and 07933 show little evidence of recent star formation. The spectra are devoid of emission lines and the continua are remarkably similar to
the normal galaxies UGC 04347 and 06648. Neither galaxy will be considered further in this study.

5.2 **COMPARISON WITH THE MODELS**

A new logarithmic absorption line flux ratio has been defined to compare the observed spectra to the models:

\[ [\text{Ca}] = \text{calcium index} \equiv \log_{10} \left( \frac{F(\text{Ca}\,\text{H} + \text{He})}{F(\text{CaK})} \right) \]

\( F(\text{CaH} + \text{He}) \) is the blended Ca II \( \lambda \)3968 and He \( \lambda \)3970 absorption line flux and \( F(\text{CaK}) \) is the Ca II \( \lambda \)3933 absorption line flux. Figure 5.3.1 is a sequence of spectra of main-sequence stars of spectral types A1 through F9 from the Jacoby et al. (1984) stellar library. Close inspection of the spectra reveals a rapid change in the relative strengths of the CaH + He and CaK absorption lines, thus, \([\text{Ca}]\) should be sensitive to main-sequence turnoff of A and F stars. Note that \([\text{Ca}]\) is nearly independent of reddening because the extinction curve varies little from 3933 to 3970 Å.

The calcium fluxes have been measured relative to linear baselines. The CaH + He baseline extends approximately from the maximum flux point between the Ca II lines to the point tangent to the continuum redward of the CaH + He line. The CaK baseline extends from the same maximum flux point to the point tangent to the continuum blueward of the CaK line. Figure 5.3.2 shows a typical pair of baselines.

The calcium index of the constant birthrate models has been plotted versus the star-burst age \( T_s \) in Figure 5.3.3.
The sudden decrease in [Ca] at ages greater than $10^8$ years indicates an increase in CaK line strength relative to CaH + He line strength and the main-sequence turnoff of stars later than spectral type A0. Indeed, it is no coincidence that the age at which the rapid downturn in [Ca] becomes obvious, $10^9$ years, is nearly the same as the main-sequence lifetime of an A1 star.

The analysis is founded on the assumption that a burst of star formation has occurred in the nucleus of a relatively old galaxy with an age of the order of $10^{10}$ years. Comparison to the models will, therefore, only be valid if the contribution of the underlying old stellar population to the observed composite spectrum is subtracted. The contribution of the star-burst to the observed spectrum of each galaxy has been isolated using the technique of template subtraction. Simple in theory, template subtraction involves subtracting from the star-burst galaxy spectrum a normal galaxy spectrum (UGC 04347 or 06648 in this case) obtained, ideally, with the same instrument.

In practice, the template spectrum must be weighted by a constant factor, the value being determined according to some criteria that measures the goodness of the spectrum fit. Pickles and Visvanathan (1985) measured the equivalent width (LEW) of the familiar Na I $\lambda\lambda 5890, 5896$ (NaD) blended doublet absorption line in the spectra of 17 normal elliptical (E) and S0 galaxies in the Fornax Cluster. Figure 5.3.5 is a plot of the LEW vs. nuclear V magnitude.
The slope of the linear fit, roughly $-1.3 \, \text{A mag}^{-1}$, implies that the depth of the absorption line varies slowly over a range of one magnitude, assuming the line profile is the same. From observed H$\alpha$ luminosities, Balzano (1983) estimates $10^7 - 10^9 \, M_\odot$ of stars have been created in the nuclei of her survey galaxies. The old populations in the nuclei of the S0 galaxies in this study probably contain at least $10^{11} \, M_\odot$ of stars, therefore, it is reasonable to assume that the NaD absorption feature observed in the star-burst spectra is due to the old population. This assumption, if correct, and the fact that the galaxies in this survey span a range of about one photographic magnitude imply that the NaD line will vanish when template subtraction is correct. In most cases, UGC 06648 was used for template subtraction because the NaD line width and profile more closely matched that of the star-burst galaxies. Those galaxies in which the NaD feature is strong enough to be used for template subtraction are shown in Figure 5.3.3.

The uncertainty in the template subtraction factor is non-trivial and must be considered in the estimate of the total uncertainty in $\text{[Ca]'}$. Let $j = H, K$ represent CaH + H$\alpha$ and CaK, respectively, $F(j)$ be the absorption line flux before template subtraction, $F_n(j)$ be the normal template galaxy absorption line flux, $F'(j)$ be the template subtracted absorption line flux, $T$ be the template subtraction factor, and $\text{[Ca]'} = \ln 10[\text{Ca}]$. The uncertainty
in template subtracted [Ca]’ is

\[
[\Delta [\text{Ca}']]^2 = \left\{ \frac{\Delta (F'(H)/F'(K))}{F'(H)/F'(K)} \right\}^2 \\
= \sum_j \left\{ \frac{\Delta F'(j)}{F'(j)} \right\}^2 \\
= \sum_j \left\{ \frac{\Delta F(j)}{F(j)} \right\}^2 + \left\{ \frac{\Delta (T_n(j))}{T_n(j)} \right\}^2 \\
= \sum_j \left\{ \frac{\Delta F(j)}{F(j)} \right\}^2 + (1-R_j)^2 \left\{ \frac{\Delta (T/T)}{T} + \frac{\Delta F_n(j)}{F_n(j)} \right\}^2
\]

where

\[
F'(j) = F(j) - T_n(j)
\]

and

\[
R_j = \frac{F'(j)}{F(j)}
\]

\( R_j \) is typically 0.75 for both CaH + He and CaK and experience has shown that \( T \) can usually be determined to no better than \( |\Delta T/T| = 0.30 \). A typical conservative random error in flux measurement of 20% was estimated by averaging the standard deviations in the galaxy fluxes. Each standard deviation in flux was computed using the deviations in the fluxes measured on different nights from the integration time weighted average flux. Setting

\[
|\Delta F(j)/F(j)| = |\Delta F_n(j)/F_n(j)| = 0.20
\]

the uncertainty is

\[
|\Delta [\text{Ca}]| = 0.18
\]

The calcium lines are close enough in wavelength that the systematic error caused by poor seeing conditions will not appreciably affect the flux ratio.

Disregarding the random error, the galaxy [Ca] is systematically smaller than even the 5 x 10^9 year models. Is the mismatch in resolution the cause of the disagreement in [Ca]? This possibility was investigated by convolving
three models with different IMFs with a 10 Å FWHM binomial distribution intended to mimic the instrumental profile. Smoothing does affect [Ca], as shown in Figure 5.3.3, but in no instance is the magnitude of the effect large enough to resolve the disagreement. Although the model points are approximately reddening independent, the same is not true of template subtracted spectra where the internal reddening of the template spectrum is different from that of the object. The internal reddening cannot be deduced from the galaxy spectra because the Hα emission line was not measured, therefore, the median observed Balmer decrement of 5.3 found by Balzano (1983) in her survey will be adopted. With a theoretical Brocklehurst (1971) case B (optically thick in the Lyman lines) Balmer decrement of 2.86 for an electron temperature of $10^4$ K and a density of $10^2$ cm$^{-3}$, the typical internal extinction for galaxies in the Balzano survey is

$$A(V) = 3.20 \log_{10} \left[ \frac{I(H\alpha)/I(H\beta)}{I(F(H\alpha)/F(H\beta))} \right] / 1.47 f(H\alpha)$$

$$= 3.20 \log_{10} \left[ \frac{2.86}{5.3} \right] / (1.47)(-0.326)$$

$$= 2 \text{ mag}$$

where $f(H\alpha) = -0.326$ was computed from the Seaton extinction curve and $I(H\alpha)/I(H\beta)$ is the theoretical decrement. The galaxies have been corrected for two magnitudes visual extinction, template subtracted, and replotted in Figure 5.3.3. [Ca] decreases in every case, exacerbating the disagreement between the models and the galaxies.

The galaxies have been compared to the exponential birthrate models in Figure 5.3.4. The decrease in calcium
index evident in models older than $10^8$ years is due to the
decrease in the rate of formation of short-lived high mass
stars. The galaxy [Ca] is still significantly smaller than
that of the models, again ignoring the random error.

The discrepancy in the calcium index may be interpreted
in several ways. If the sharp downward trend in [Ca]
continues in models with ages greater than $5 \times 10^9$ years,
then the data might imply that the star-burst populations in
all 5 galaxies are older than $5 \times 10^9$ years regardless of
the IMF slope or the exact functional form of the relative
birthrate. This is not an unprecedented result; Huchra
(1977b) found that star-bursts in the bluest non-Seyfert
Markarian galaxies could be $\sim 10^{10}$ years old under certain
conditions. Nevertheless, it seems physically implausible
that the young populations in star-burst galaxies are, as a
group, greater than $5 \times 10^9$ years old. The modelling
assumptions, on the other hand, may be incorrect. The real
IMF and birthrate may be different than assumed and both
parameters may even vary from galaxy to galaxy. The
possibility of multiple episodes of star formation has not
been considered. The metallicity, assumed to be solar in
the models, may actually be less than solar if the galaxies
have accreted gas from external sources or greater than
solar if the gas has been cycled through multiple
generations of stars. Metal abundance greater than solar
will enhance stellar atmosphere line blanketing, resulting
in deeper absorption lines and redder continuum colors in
the composite models. At the other extreme, the models will be underluminous in the V band, have relatively weak absorption lines, and will show an ultraviolet excess $\delta(U-B)$ for metallicity less than solar. Stellar winds affect the evolutionary tracks of high mass stars. For example, evolutionary time scales lengthen by no more than 5% and effective temperature generally does not change significantly when mass loss is included in the calculations of Brunish and Truran (1982), but the luminosity of the 40 solar mass model decreases by as much as 39%. Overall, the effect on the composite models will still be of secondary importance compared to the effect of metallicity because there are relatively few high mass stars.
6. **SUMMARY AND RECOMMENDATIONS**

Of the 10 S0 Markarian galaxies observed and analyzed in this study, 7 appear to be legitimate star-burst galaxies. All 7 nuclei exhibit qualitative spectral characteristics that are almost certainly due to A type stars:

1) a pronounced stellar-like blue continuum
2) deep, prominent Balmer absorption lines
3) an obvious Balmer discontinuity

These same nuclei also possess strong Hα, Hβ, [O III], and [O III] emission lines, although not all of these lines necessarily appear together in every spectrum. The emission lines in the spectra of UGC 01157, 04902, 06570, and 12618 probably originate in complexes of H II regions photoionized by young OB stars. None of the galaxies show obvious [O I] λ6300 line emission, possibly eliminating LINER activity, as defined by Heckman (1980), as the dominate energy source.

There is also no compelling optical evidence of a non-thermal power-law component in the observed nuclear continua. No useful information on the emission line widths or profiles could be gleaned from the data because the lines were unresolved. Emission line characteristics are now such important diagnostic tools in active galaxy research that high resolution observations of the 7 tentatively identified star-burst galaxies are highly recommended and would help reinforce the star-burst classification.

There is little evidence of recent star formation in
the nuclei of the remaining 3 Markarian galaxies. [O III] line emission is present in the spectrum of UGC 04933 and the calcium absorption lines are slightly stronger compared to normal (old) galaxies UGC 04347 and 06648, but [Ca] would be negative for UGC 04933 and the normal galaxies whereas [Ca] is apparently invariably positive for the confirmed star-burst galaxies. Nuclear star formation most likely occurred too long ago for UGC 04933 to be considered a star-burst galaxy in the conventional sense. The continua of UGC 02093 and 07933 are strikingly similar to the normal galaxy continua. In addition, the emission lines one associates with recent star formation are totally absent in the nuclei of both galaxies. It is not obvious why either galaxy was included in the Markarian lists.

The spectra of simple composite models with IMF exponents of -1, -2.5, and -4 and constant and exponentially decreasing (e-folding time of 5 x 10^9 years) relative birthrates do not match the observed spectra of UGC 03201, 03265, 05292, 06570, and 12618. The template subtracted galaxy calcium index is smaller than that of the models. Sensitive to internal reddening, [Ca] can be better determined by obtaining the Hα emission line flux for each galaxy rather than adopting the Balzano (1983) median observed Balmer decrement for all of the galaxies.

Two explanations are advanced to account for the difference in the measured galaxy and model calcium indices. The young stellar populations in the nuclei of all 5
galaxies may have ages greater than \( 5 \times 10^9 \) years for any of the IMF/birthrate combinations considered in this study. A second measured quantity such as photometric (B-V) color will be needed to derive specific information on the IMF and birthrate from comparison with the models. An alternative to the preceding interpretation of the data is the possibility that the input parameters in the modelling are inappropriate for S0 star-burst nuclei. IMFs and birthrates similar to those found in the solar neighborhood may not accurately describe star formation in these galaxies. One burst of star formation has been assumed in the modelling even though multiple bursts may actually have occurred. The assumption of solar metal abundance may not be justified. A parametric study of the effect of metallicity on the model spectra might help resolve this issue. Finally, stellar winds, neglected in the models, may actually play an important role in the evolution of high mass stars.
FIGURE CAPTIONS

Figure 2.2.1. The McDonald Observatory IIDS used with the 2.7m telescope is similar to the Lick Observatory IIDS shown in this figure.

Figure 2.2.2. Spectral response curves of some common UV-visible photoemitters.

Figure 3.1.1. Schematic diagram of the RUPPS data reduction process. Relevant RUPPS routines are indicated in parentheses.

Figure 3.3.1. The December 14th A aperture quartz spectrum normalized with a 21st order Legendre polynomial fit. Notice the oscillation over the first 500 channels.

Figure 3.3.2. The December 14th A aperture quartz spectrum normalized by separately fitting 21st order Legendre polynomials to the first and last half of the spectrum. The oscillation in Figure 3.3.1 has essentially been eliminated.

Figure 3.4.1. Residuals to the December 15th A aperture polynomial dispersion solution. The most recent version (Aug. 1986) of the RUPPS WLFIT routine allows the user to add or delete emission lines at will after viewing the residuals.

Figure 3.6.1. The December 14th B aperture instrumental sensitivity curve. Standard stars HZ 15, Feige 34, and Feige 56 (B5, sd0, and B5p, respectively; Stone (1977) and references therein) were used to derive the curve. The sensitivity sharply peaks at about 5000 A and rapidly decreases in the blue.

Figures 3.7.1 - 3.7.12. Reduced galaxy spectra. All spectra have been corrected for galactic extinction, but have not been smoothed.

Figures 4.2.1 - 4.2.5. A sample sequence of model spectra with ages of $0$, $10^7$, $10^8$, $10^9$, and $5 \times 10^9$ years. The IMF has an exponent of -2.5 and the relative birthrate is constant. Individual stellar spectra used to construct the composite model spectra have been corrected to a common distance of 10 pc.
Figure 4.2.6. Comparison of the \(10^8\) and \(10^9\) year constant birthrate composite models to the models of Huchra (1977b) with nearly constant (e-folding time \(\geq 1.5 \times 10^{10}\) years) birthrate. Huchra model ages: triangles = \(2 \times 10^8\) years; open circles = \(1.2 \times 10^9\) years. Numbers next to the Huchra model points are the IMF exponents used to construct the models. Composite model IMF exponents: "+" = -1; "x" = -2.5; squares = -4.

Figure 4.2.7. Comparison of the \(5 \times 10^9\) year constant and exponentially decreasing birthrate composite models to the \(1.2 \times 10^{10}\) constant and exponentially decreasing (e-folding time of \(5 \times 10^9\) years) birthrate models of Huchra (1977b). Huchra model birthrates: triangles = constant; open circles = exponential. All other numbers and symbols have the same meanings as in Figure 4.2.6. The Huchra models are systematically redder in (B-V) because they are older by greater than a factor of 2.

Figure 5.3.1. A sample of main-sequence A and F stellar spectra from the Jacoby et al. (1984) library. The CaH + H\(\delta\) to CaK absorption line flux ratio varies rapidly over this range of spectral types.

Figure 5.3.2. A sample pair of baselines used for measurement of the logarithmic ratio [Ca].

Figure 5.3.3. Comparison of UGC 03201, 03265, 05292, 06570, and 12618 to the constant birthrate composite models. Model symbols are the same as in Figure 4.2.6. The uncertainty in [Ca] (not shown) is \(\pm 0.18\). Arrows next to the models indicate the effect of convolution with a 10 Å FWHM binomial distribution. Galaxy calcium indices indicated on the right ordinate have been measured after correction for 2 magnitudes visual internal extinction.

Figure 5.3.4. Comparison of UGC 03201, 03265, 05292, 06570, and 12618 to the exponential birthrate composite models. Model symbols are the same as in Figure 5.3.3.
Figure 5.3.5. The Pickles and Visvanathan (1985) plot of the NaD doublet absorption line EW vs. nuclear V magnitude ($V_{\text{nuc}}$) for 17 normal E (filled circles) and S0 (open circles) galaxies. The linear regression slope is roughly $-1.3 \ A V_{\text{nuc}}^{-1}$. 
Figure 2.2.1
Figure 2.2.2
Figure 3.1.1
Figure 3.3.1

Figure 3.3.2
Figure 3.4.1

X = unity weight
□ = increased weight
Figure 3.7.1

Figure 3.7.2
Figure 3.7.3

Figure 3.7.4
Figure 3.7.7

Figure 3.7.8
Figure 3.7.9

Figure 3.7.10
Figure 3.7.11

Figure 3.7.12
$n = 2.5$, constant $b(t)$, 10 million years.
$n = 2.5$, constant $b(t)$, 1 billion years

Figure 4.2.4
Figure 4.2.6
Figure 4.2.1
Figure 5.3.1

Relative F

WAVELENGTH (Å)

3500 4300 5500 6500 7500

31 F0 V
32 F2 V
33 F4 V
34 F5 V
35 F6 V
37 F7 V
40 F8 V
41 F9 V

31 A0 V
21 A2 V
24 A3 V
25 A5 V
26 A6 V
28 A7 V
29 A8 V
30 A9 V

Ca + Hc
CuK

Relative F
Figure 5.3.5
TABLE CAPTIONS

Table 2.1.1. General information, taken mostly from the Uppsala General Catalogue of Galaxies by Nilson (1973), on the galaxies selected for this study. The diameters have been estimated from the blue Palomar Sky Survey prints. Nilson (1973) does not formally define the meaning of the "?" and ":" designations. If the meanings are the same as the Second Reference Catalogue of Bright Galaxies by de Vaucouleurs et al. (1976), then "?" = uncertain and ":" = doubtful. Nilson (1973) has adopted the apparent photographic magnitudes tabulated in the Catalogue of Selected Compact Galaxies and of Post-Eruptive Galaxies by Zwicky (1971). The heliocentric velocities of UGC 02093, 03201, 03265, and 04347 are from J. Huchra (1982 and later private communications to L. L. Dressel); all others are from the CfA survey of Huchra (1983).

Table 2.3.1. Typical photon statistics assuming a 2 counts/photon multiplex factor.

Table 3.5.1. The standard McDonald Observatory atmospheric extinction coefficients measured by Hiltner (1956).

Table 3.7.1. Comparison of the galactic extinction curve of Savage and Mathis (1979) and Seaton (1979) with \( R = A(V)/E(B-V) = 3.1 \) and 3.20, respectively. The Seaton curve was chosen for reduction of the data.

Table 3.7.2. Verification of the published reddening values of Burstein and Heiles (1984). The new galactic coordinates \( l_{II} \) and \( b_{II} \) are in degrees, \( R \) is the galaxy count residual from the contour map of Heiles (1976), and \( N_{H} \) is the galactic H I column density from the 21 cm contour map of Heiles (1975). Published values were adopted for all galaxies except UGC 03265. The difference between calculated and published values for UGC 03265 could not be ascribed to error in interpolation of the contour maps, therefore, an independent estimate of 0.120 was adopted.
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Table 2.1.1
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Table 3.7.2
REFERENCES


