Chapter I

INTRODUCTION

The study of the composition and evolution of galaxies is one of far reaching importance for astronomy. The traceback of the evolution of galaxies with time is indeed the single most important sequence chronicling the evolution of the known universe, since the early epoch of formation of galaxies. Since their formation galaxies have evolved, due to the evolution of constituent stars, due to recurring formation of new generations of stars from matter left over after the initial epoch of formation, matter expelled by evolving stars into the interstellar medium and matter falling into the galaxy from the environment. The evolution of galaxies is also greatly influenced by dynamical interaction between neighbouring galaxies. Unravelling this complex scenario in terms of present day understanding of these aspects of evolution is an arduous task and is perhaps one of the most important aims of extragalactic research.

From a pragmatic point of view the dynamical interaction between galaxies and its effect on evolution is not yet a tractable problem; further, the question of large amounts of gaseous matter falling
into galaxies and ensuing large scale star-formation activity is comparatively rare and detailed observations do not exist to permit systematic studies of such events and their influence on galaxy evolution. The role that the dynamics of large star-forming clouds plays in galaxy evolution is also not clearly understood. It would thus seem right for the present that studies of galaxy evolution have largely concentrated on 'normal' galaxies showing no or minimal signs of violent star formation, non-thermal activity or dynamical interaction with neighbouring galaxies. The vast majority of galaxies are of this type and in this dissertation we shall be concerned with such objects.

I.1. The Stellar Content of Galaxies:

The light of galaxies (from the ultraviolet to the near infrared region of the spectrum) comes largely from the photospheres of the stars constituting them. Since formation, the light from any given galaxy i.e. the integrated spectral energy distribution (SED), has continuously changed simply because the stellar content has continuously changed. The stellar content changes since stars evolve in accordance with their masses and heavy element abundances, more massive stars dying earlier and being replaced by less massive stars in the production of the integrated radiation.
The stellar content further changes if new generations are evolving.

The determination of the stellar content of galaxies is thus an important aspect of studies of the evolution of galaxies. Except for the nearest bright galaxies where some of the brightest stars can be resolved, such studies are entirely confined to an analysis of the integrated light from a mixture of unresolved stellar components. The essential aim is to determine the relative proportions of these components. The technique of population synthesis, in various forms, has been used to synthesize the photometric colours, the energy distributions and the spectra of galaxies, from a mixture of stars of different spectral types, luminosity classes and element abundances, for which the corresponding data have also been collected.

The distribution of stars on the Hertzsprung-Russell (HR) diagram thus derived allows the determination of several parameters including the average metallicity of the galaxy, the main sequence turnoff point and the corresponding age of the last major star formation activity, and estimates of subsequent star formation rates from relative proportions of young stars. These parameters, coupled with models for the evolution of galaxies, enables the determination (to the extent permitted by current knowledge of stellar
evolution) of the history of star formation (the star formation rate or SFR at different times) and the initial mass function (IMF).

1.2. Determination of the stellar content of galaxies:

The essential technique of matching observed spectral properties of galaxies with a combination of corresponding data for known individual stars in our Galaxy is fairly old. The first such attempt was that of Whipple, made over fifty years ago (Whipple 1935). He outlined a method for measuring equivalent widths of lines and colours for a galaxy and for many stars of different spectral classes and luminosities; the numbers of the latter were adjusted and an integrated spectrum computed to obtain the best fit to the galaxy observations. The large data base of observations of line equivalent widths and colours covering all portions of the HR diagram and similar accurate data for galaxies was just not available at the time; so in practice this work could not be carried out, to the required degree of completeness.

1.2.1. Spectroscopy, equivalent widths and line ratios:

Early attempts to assess the stellar content of galaxies from spectroscopic observations include the
work of Morgan and Mayall (1957). From low dispersion spectra they concluded that the equivalent spectral type of the galaxies changed with the wavelength range observed, becoming progressively earlier at shorter wavelengths. They used the MK (Yerkes) system, following the general schemes of classification of composite systems for globular clusters (Morgan 1936), to assign equivalent spectral types to galaxies. For M31 they derived a type of around F8 for $\lambda 3900\AA$, the 'cyanogen giant stars' gG8 to gK3 for $\lambda 3880\AA$ to 4300$\AA$, types K4 to K5 for $\lambda 4600\AA$ and M giants in the red and near infrared. Their work highlighted the need for wide spectral coverage in attempting to explain the stellar content of galaxies.

Following the suggestion of Whipple (1935), that equivalent widths of lines are more sensitive than colours in determining the stellar content, G. and A. de Vaucouleurs (1958, 1959) made an attempt to quantitatively synthesize a spectrum of the Large Magellanic Cloud in the range $\lambda 3700-4900\AA$. Their model which best fitted the observed spectrum required 62% of the blue light to come from B stars, 10% from A stars, 5% from F stars and 17% from evolved G and K stars. The discovery of the He I line at 3820$\AA$ in their spectrum of the LMC led to the requirement of a large member of B stars.
Spinrad (1962) used line strengths in the spectral region $\lambda \sim 4000-6800\AA$, to study the stellar content in several galaxies. He used several important luminosity discriminants in the green and near-infrared region of the spectrum. Using these luminosity dependent spectral lines (especially the NaI 'D' lines), he gave a model for the nucleus of M31 and for giant elliptical galaxies, where most of the light was accounted for by an old population I base with a significant fraction of late spectral type, red dwarf stars added.

The spectroscopic studies mentioned above and some others not specifically referred to here, have all been done photographically. It must be pointed out that the photographic method has several disadvantages: night sky emission cannot be easily subtracted, emulsions have low quantum efficiency, especially in the near-infrared region of the spectrum and the process of calibrating from densities to relative intensities introduces further errors. Also, it is usually not possible to obtain accurate absolute fluxes using observations of standard stars with known fluxes. However, photographic techniques can be applied for limited spectral regions observed at higher spectral resolutions, as has been done by Rose (1985).

Rose used photographic image tube spectra in the region $\lambda \sim 3400$ to $4500\AA$ with a resolution of $2.5\AA$, to
form relative line strength ratios of neighbouring lines which are used as indicators of temperature, luminosity and metal abundance. He found that hot stars contributed only 2% to the integrated spectrum of elliptical galaxies at $\lambda \sim 4000\AA$. The line indices CaII H + Hg /Ca II K could be matched by including a small metal-poor population that contributes 8% of the light at 4000\AA. He also showed that the presence of a substantial fraction of stars of intermediate age (as suggested in O'Connell 1980) in elliptical galaxies differentiates between them and the metal-rich Galactic globular clusters. Williams (1976), also used photographic image tube spectra in the range $\lambda \sim 3800$ to 6800\AA with a resolution of 2\AA, to synthesize observed line indices in the nuclear regions of ten galaxies.

1.2.2. Photometry:

The first quantitative attempt to use photometric colours for obtaining the stellar content of galaxies involved a six-colour photometric system by Stebbins and Whitford (1948) covering the wavelength range between 3500\AA and 10300\AA with average filter bandpasses of around 1000\AA. Comparison of their colours for some bright elliptical galaxies with a dwarf mid-G spectral type star gave colour excesses at both the ultraviolet and infrared wavelengths. Though the coverage of the HR diagram was again incomplete, the results showed
that broad-band colours of a galaxy are fairly insensitive to differences in stellar population models.

Intermediate band filter photometry has been used by several observers in attempting population synthesis (Wood 1966, 1969; Mc Clure and van den Bergh 1968; Faber 1972). Filters with band passes of the order of 100Å were generally chosen to cover several points in the continuum as well as spectral features discriminating between stellar types. Wood (1966) employed twelve-colour observations to find that models patterned after an old galactic cluster population like M67, enriched with a few late-type giants, many dwarfs of late spectral type and some horizontal branch stars fitted the galaxy observations well.

Mc Clure and van den Bergh (1968) observed over 200 stars, 70 clusters and 56 galaxies on an intermediate band system covering the Balmer discontinuity, the discontinuity at 4000Å due to line blanketing, the violet CN absorption and the G-band due to MgH. They derived reddening-free indices which were used as classification criteria for different types of stars and the metallicities of globular clusters. These indices, however, did not permit segregation of the effects of stellar metal abundance on the integrated
light of the cluster and the effects produced by the distribution of stars in the cluster colour-magnitude diagram. By studying the cyanogen index, they concluded that light from the semistellar nucleus of M31 and the core of the elliptical galaxy NGC 4472 was dominated by stars of very high metal abundance (cyanogen rich giant stars).

Faber (1972) used the method of quadratic programming to synthesize the stellar populations of M31, M32 and M81 and typical elliptical galaxies. She applied the synthesis technique to both 10-colour photometry as well as to 38-colour spectrophotometric indices (Spinrad and Taylor 1971). She concluded, in essence, that the technique yields good mean line strengths in external galaxies. However, her work did not confirm an enriched late spectral type dwarf sequence and she stated that the technique was not sensitive to the relative numbers of lower main sequence stars between K0V and M7V. The dwarf to giant star ratios and the mass to luminosity ratios were hence very uncertain.

Synthesis using broad band or intermediate band photometric data has several disadvantages; it is difficult to reproduce photometric systems accurately at different observatories, the filters and bandpasses must be chosen with prior knowledge of which spectral features and continuum points to look for. The spectral
features of interest can shift out of the filter band-passes as galaxies of higher redshift are observed. Moreover, as the studies discussed above indicate, even intermediate band photometry yields colours and indices which are not sensitive to all the possible ingredients in the stellar mix making up a typical galaxy.

1.2.3. Spectrophotometry:

Since photographic emulsions used in traditional spectroscopy are difficult to calibrate accurately and are not sensitive enough in some wavelength regions of interest (e.g., the near infrared), and since broad and intermediate band photometry does not provide sufficient coverage of the spectrum to discriminate between various stellar types, the spectrophotometer or spectrum scanner (as it is often called) became an obvious choice for galaxy spectrum synthesis.

In a typical scanner, the light is dispersed by a grating and a portion of the spectrum as determined by an exit slit is sampled by a photomultiplier tube. By rotating the grating in steps, the entire spectrum (as limited by the grating and photomultiplier efficiency) can be scanned or selected points in the spectrum can be sampled in a manner similar to photometry. In the last decade and a half solid state
array detectors such as the Reticon array and the charge coupled device (CCD) arrays have enabled the sampling of a large number of adjacent points in the spectrum simultaneously, with the 'bandpass' of photometry being replaced by the dimension (along the dispersion direction) of each pixel in the array.

The earliest attempts in scanning the spectrum of galaxies are those of Code (1959) and van den Bergh and Henry (1962). From the strength of the ultraviolet and blue CN bands, they both concluded that late-type giant stars contributed a large portion of the light from the nucleus of M31.

Spinrad & Taylor (1971) did very comprehensive work in deriving the population models for the nuclear regions of the galaxies M31, M32 and M81. They used the scanner as a tunable filter and measured fluxes at 36 points in the spectrum between 3600Å and 10700Å. The passband for the measurements was 16Å for \( \lambda < 5360Å \) and 32Å for \( \lambda > 5360Å \). These passbands covered many continuum points as well as luminosity and temperature sensitive spectral lines. The stellar data base covered 37 distinct stellar types. They found an appreciable contribution to the light from M31 to be from lower main sequence dwarf stars (as late as M8 V), giving a ratio of the total mass from stars to the total visible light from them (M/L ratio)
of 44. Their model for M31 required strong-lined giant stars and metal weak stars were completely excluded. The main sequence turn off derived was at GO V, indicating an old population. Their model for M81 (not considering emission lines in the spectrum) was similar to that for M31 except that more giant M stars were required. For M32 they did not require as many late type dwarf stars as for M31 and the strong lined giant stars were not required to be present.

Another comprehensive study applying a population synthesis technique based on linear programming to narrow band spectrophotometric data was that of O'Connell (1976). He used a spectrum scanner to cover the spectral region from 3000 to 10800\(\AA\) with bandpasses of about 16\(\AA\) for \(\lambda \leq 5050\AA\), 26\(\AA\) for 5050\(\AA\) \(\leq \lambda \leq 7400\AA\) and 130\(\AA\) for longer wavelengths. The stellar data base covered 48 different types (O'Connell 1973) including 'super-metal-rich' stars and metal poor stars. The galaxies studied were the elliptical galaxies NGC 4374, NGC 4472 (M49) and NGC 4552 (M89). O'Connell found that M type giant stars dominated over M dwarf stars throughout the spectrum and excluded the possibility of a mass to light ratio greater than 30. His best models gave a \(2 \leq M/L \leq 15\). The synthesis model used constraints which ensured continuity in the HR diagram and which placed limits on the relative numbers
of stars in various evolutionary stages. These constraints were derived from theoretical and empirical tracks of evolution in the giant and subgiant branches. The constraints for the evolved stars, however, had large uncertainties due to the absence of evolutionary tracks (particularly, the giant branch) which match well the tracks of well-observed old clusters in the Galaxy. The models yielded a small range of main sequence turnoffs (dependent on the relative rates of main sequence and subgiant evolution) implying that the bulk of the stars in the galaxies observed formed 8 to $11 \times 10^9$ years ago, with subsequent star formation at a low rate until about $4 \times 10^9$ years ago. There was no evidence of a significant contribution from population II stars whereas distinct enhancements of Na I and Mg I were found in the galaxies. O'Connell's main conclusions vis-a-vis contribution to the integrated light were: 20 to 30 per cent of the light in the V band from KO-3 giants, over 15 per cent of the near-infrared light from M giants. The model does not permit a satisfactory fit to both the continuum and absorption indices sensitive to luminosity in M stars. He also found that the inclusion of mainly normal (solar) abundance stars in the stellar data base used for the synthesis made it difficult to disentangle the effects of age and metallicity.
Gunn, Stryker and Tinsley (1981) used an evolutionary synthesis technique to derive population models for the galaxies NGC 545, 4472, 4486 (M87), 4486B, 4874, 4889, 6166 and M31. They used scanner data to cover 509 points in the spectrum between $\lambda 3130\AA$ to $10800\AA$ with a resolution of $20\AA$ in the region $\lambda < 5400\AA$ and $40\AA$ at longer wavelengths. The components chosen to fit the galaxy observations were certain populations in the HR diagram, such as theoretical isochrones for old populations, the entire solar neighbourhood young population etc., as opposed to groups of stars in small regions of the HR diagram. The basic conclusions were similar to earlier work: giant elliptical galaxies and the centre of M31 are dominated by an old metal-rich population (the light being mainly from strong-lined giant stars), with some hotter stars above the main-sequence turnoff point (as in Faber 1977 and O'Connell 1976). As opposed to O'Connell (1976, 1980) the colour at turnoff is redder, being $B-V = 0.80 \pm 0.03$, and, depending on the composition this leads to turn-off ages in the range $9$ to $14 \times 10^9$ years. The question of the nature of the hot stars was not resolved, though the authors favoured blue stragglers and young stars over horizontal branch stars, since the metal rich population would produce too few of the latter.
Pickles (1985) performed differential population synthesis for 12 elliptical and five lenticular galaxies, all in the Fornax cluster of galaxies. His observations covered the range \( \lambda 3600 \ang{} \) to \( 10,000 \ang{} \) with spectral resolutions of 10 to \( 20 \ang{} \). He used the technique of constrained minimisation to minimize residuals of the fit to observed galaxy spectral energy distributions by combinations of different types of stars from a library of 48 stellar groups. The data for the stellar groups did not, in all cases, have the resolution of 10 to \( 20 \ang{} \), especially beyond \( 8600 \ang{} \), where lower resolution data (50\ang{} bandpass) was used. He found the main sequence turn off groups to be quite young, indicating substantial star formation in all the early-type galaxies in the Fornax cluster for a period of 6 to 10 \( \times 10^9 \) years after the epoch of globular cluster formation. The results generally indicate more of continuing star formation in the brighter galaxies. Three of the brighter ellipticals showed the presence of a significant hot star component, most likely due to early type upper main sequence stars, implying some current star formation. However, the evolutionary status of these hot blue stars was not absolutely certain; they could be upper main sequence stars or evolved stars on the horizontal branch. The best solutions showed about 40 to 50 per cent of the light in the visual
band (V) to be from G-K dwarfs in all ellipticals. The contribution from G-K giant stars decreased from about 50 per cent at V for the brightest elliptical galaxies to about 20 per cent for the faintest. It was not possible to get a unique proportion of M giant and dwarf stars which best fitted the near-infrared data. The mass to light ratio determined was thus rather uncertain. It is instructive to remark here that the late type dwarf-star-enriched models of Spinrad and Taylor (1971), discussed earlier, have not been corroborated by others. O'Connell (1974, 1976) found that M giant stars dominated the light from elliptical galaxies. The strength of the CO band at 2.3 mm in elliptical galaxies, which is a sensitive function of luminosity in a positive sense, indicates a giant dominated population (Frogel et al 1975, Baldwin et al 1973). On the other hand studies of indices reflecting the strength of the Wing-Ford (WF) band due to FeH at 9916 Å, which is significant only in dwarf stars of type M5 and later, revealed no detectable contribution from such stars in galaxies (Whitford 1977), thus ruling out very late-type dwarf dominated populations. The WF band was detected in higher resolution spectra of the nuclei of M31 and of M32 by Cohen (1978), who also studied the strengths of other luminosity sensitive features (the near-infrared doublet due to Na I, the Ca II triplet and TiO bands in the near-
infrared region); she did not, however, find any substantial dwarf enrichment in these galaxies.

Synthesis models for stellar populations in galaxies have been constructed by others, not discussed here in detail (Pritchett 1977, Aaronson et al 1978, Wyse 1985). Since the first ultraviolet observations of elliptical galaxies with the International Ultraviolet Explorer (IUE) Satellite, it became clear that a mix of a purely metal rich population of stars could not account for the high flux in the region $\lambda 2000\AA$ to $3300\AA$ (Bruzual 1983). It does seem, however, that the basic problems remain in the interpretation of integrated spectra of early type galaxies i.e. the source of the excess light in the blue and the ultraviolet region of the spectrum, the age and metallicity of the dominant population of stars in these systems and the relative proportions of cool giant and dwarf stars.

1.3. Aims of Population Synthesis

The study of the evolution of galaxies (specifically, early-type 'normal' galaxies as discussed at the beginning of this Chapter), requires, as inputs from analyses of observations, the stellar content of galaxies at different epochs since their formation. The change in the stellar content can then be correlated with and interpreted in terms of current theories
of stellar evolution. The technique of population synthesis aims at determining, from observations, the number of stars in an absolute magnitude (luminosity) range $dM_v$ around $M_v$, a spectral type range $dS$ around $S$ and a metallicity range $dZ$ around $Z$, as a function of $M_v$, $S$ and $Z$ i.e. $N(M_v, S, Z)$. In the general case, the luminosity of a galaxy at any wavelength $\lambda$ would then be

$$L_\lambda = \iiint \frac{-0.4^{M_v}}{Z S M_v} N(M_v, S, Z) dM_v dS dZ$$

The above procedure, a static one, thus divides stars into various groups of luminosity, effective temperature and chemical composition and tries to obtain a best fit to the observed photometric properties of the galaxy in question using a mix of stars of different groups. The best fit, however, is strongly determined by constraints imposed on relative proportions of different kinds of stars, which are used to avoid non-unique solutions (Tinsley 1980).

The method of evolutionary population synthesis, on the other hand, uses the knowledge of stellar evolution to determine at any time, given a scenario of star formation (whether one time or continuous), the distribution of stars on the HR diagram. The observed photometric and spectral properties of this stellar
distribution are then compared with corresponding properties of the galaxy observed. In this method, the distribution of stars is thus consistent with stellar evolutionary requirements and no constraints are required in the fitting of the data. The major lacuna here, is that detailed evolutionary tracks are not available for all species of stars expected to be present in galaxies in significant numbers. Also, the models generally use various empirical forms of the function determining the formation of stars (the SFR or star formation rate) of different species (Tinsley 1980, Arimoto and Yoshii 1986, Renzini and Buzzoni 1986, Barbaro and Olivi 1986 and references therein). In the general case, if \( f(m, t, Z) \) and \( C(m, t, Z) \) denote the flux of a star (of mass, \( m \), age \( t \) and chemical composition \( Z \)) and the birthrate of stars (of mass \( m \) and composition \( Z \) at time \( t \)) respectively, then the integrated flux of a galaxy (see Barbaro and Olivi, 1986) of age \( T \) is:

\[
F_\lambda(T) = \int_T^{\infty} \int_{m_u}^{m_l} \int_{Z_u}^{Z_l} C(m,t,Z) f_\lambda(m,t,Z) \, dt \, dmdZ
\]

where \( m_u, m_l \) are upper and lower mass limits of stars and \( Z_u, Z_l \) are upper and lower limits on the heavy element abundances in stars. Essentially, since \( f_\lambda \) and \( F_\lambda \) can be observed, various forms of \( C(m,t,Z) \)
can be used, in conjunction with stellar evolution theory to derive the distribution of stars in the HR diagram, whose integrated $f_\lambda$ best matches $F_\lambda$ for the galaxy.

1.4. Outline of this dissertation

This dissertation describes the observations, reductions and final analyses comprising a study of stellar populations in early type galaxies using the techniques of population synthesis. The plan of the dissertation is as follows:

The second chapter describes the telescopes and instrumentation used for observations at the Vainu Bappu Observatory, Kavalur (South India) and at the European Southern Observatory (Chile).

The third chapter discusses the considerations that went into the plan of observations, the observing procedures used and summarises information about the objects observed.

The fourth chapter describes, in some detail, the procedures used in reducing the data to a form amenable to analysis. The spectra of the stellar ingredients for population synthesis and of the galaxies are discussed and displayed.
The fifth chapter presents a brief description of the stellar and galaxy spectra with emphasis on spectral features particularly useful in spectral and luminosity classification. The techniques of population synthesis employed are also discussed, details of the actual synthesis runs performed are given and the results for the galaxies are presented.

The last chapter outlines the work done in the thesis and summarizes the principal results. Plans for future work to be undertaken are also discussed.