Abstract

This thesis is about the optical and near-infrared morphology of low-redshift \( z < 0.3 \) radio galaxies. It is based on observations of a radio selected sample of galaxies from the Molonglo Reference Catalogue. We have observed these galaxies with the 1.0m and 2.5m telescopes at the Las Campanas Observatory in Chile, using broad band \( B \) and \( R \) and near-infrared \( K' \) filters. The morphology and structure of the galaxies have been studied through a series of steps involving the analysis of the 2-dimensional brightness distribution of the galaxies. We outline below the motivation behind this work, summarize the techniques and mention important results.

Traditionally, radio galaxies have been believed to be ellipticals consisting of a coeval population of old stars, and almost no dust or gas. However, photometric studies carried out over the past few years have demonstrated that elliptical galaxies not only have dust and/or gas, but also possess fine structure indicating some amount of activity in the past \( \sim 10^2 \) million years. Radio galaxies host an active galactic nucleus (AGN) and are associated with highly energetic phenomena like the radio jets which transport a very large amount of energy over hundreds of kiloparsecs. Such phenomena are likely to be associated with morphological features not found in normal elliptical galaxies. A motivation of this thesis has been to identify such features in the radio galaxies.

We have (1) studied the 2-dimensional brightness distribution, in the \( B \), \( R \) and \( K' \) bands, of the galaxies in the plane of the sky by fitting elliptical shapes to isophotes; (2) fitted standard bulge and disk laws to 1-dimensional major-axis profiles extracted from the elliptical model isophotes; (3) studied distributions of fitted parameters and correlations between them; (4) studied color distribution in the galaxies using different techniques; (5) correlated radio, optical and near-IR properties; (6) used morphological image processing techniques to identify faint features and (7) carried out simulations and modeling to confirm the validity of the extracted features.
In order to differentiate between the properties of radio galaxies as a class from those of normal galaxies, we have compared radio galaxy properties with those of a control sample consisting of non-radio selected early-type galaxies. The comparison sample has been drawn from the CCD frames of the radio galaxies. This ensures that the radio and control samples are subject to identical data processing and photometric calibration. Comparison has also been made with properties of galaxies from the literature wherever adequate data has been available.

We begin the thesis by presenting an overview of the properties of radio galaxies and elliptical galaxies. We explain the importance of the study of the morphology of galaxies to the understanding of the physical phenomena that give rise to these morphologies.

We then go on to describe in detail (1) the sample that has been used for the present study; (2) the instruments used and the data acquisition techniques; (3) preprocessing to remove the signature of the instruments from the data; (4) calibration using the observations of standard stars and (5) various corrections applied to the data to account for the Galactic extinction and the redshift of the object. Finally we describe the control sample used in this thesis.

We next discuss the isophotal shapes of the program and control galaxies. We expect the projected shapes of isophotes of elliptical galaxies to be ellipses. We describe a program, which, for an isophote at a given semi-major axis length, provides the best fitting ellipse characterized by an ellipticity and position angle. A series of such ellipses with different semi-major axis lengths then provide an intensity profile for the galaxy image. The deviation of the isophotes from the best fitting ellipses yield important parameters which are indicative of disky or boxy nature of the isophotes. We describe the various correlations that we find amongst the parameters which are obtained from the ellipse fitting exercise. These parameters provide useful information about the 3-D shapes of the galaxies. A section is devoted to the present
understanding of the 3-D intensity distribution in elliptical galaxies.

The radial intensity profile of a galaxy is well described by two components viz. the bulge, which is well approximated by de Vaucouleurs' \( r^{1/4} \) law, and the disk which is exponential in nature. Each of these components is characterized by a scale length (\( r_e \) for the bulge, \( r_s \) for the disk) and the intensity at a characteristic radius. In case of an elliptical galaxy, the bulge dominates over the disk. In fact, until a few years ago, it was believed that elliptical galaxies do not contain a disk component at all. We have obtained the scale lengths for each galaxy by fitting the intensity profile, in the different filters available, with a bulge-disk combination. Such a decomposition into bulge and disk parameters plays an important role in determining various properties related to the morphology. We present details of the technique along with a working algorithm and its implementation.

We then describe the distribution of various fitted parameters and the relations between them. Since the bulge is dominant in ellipticals, we particularly emphasize bulge related properties. While absorption due to dust, age and metallicity tend to redden a galaxy in its central region, star formation occurring near the center causes it to have a greater concentration of blue light there. All these factors affect the scale lengths, and the scale lengths in different filters (e.g. \( B, R, K' \)) then indicate the more dominant factor in each filter. For normal galaxies, one expects that \( r_e \) is larger at shorter wavelengths since normal age and metallicity effects dominate over star formation. From a study of bulge scale lengths we show that radio galaxies tend to have excess blue colors in their central regions compared to normal ellipticals. The origin of the extra blue light, seen over several kpc from the centers of these galaxies, is likely to be the formation of stars over the last several 100 Myr. The modeling that we have carried out in this context is described later on in the thesis.

Galaxies that have a disk-to-bulge ratio (\( D/B \) > 0.3) are classified as lenticulars or spirals. We find that ~20% of the galaxies in our radio sample
have $D/B > 0.3$. We have investigated these *disky ellipticals* in detail. In two cases we find that the $D/B$ value, as well as parameters describing the disk-like structure, are similar to those obtained for $Sb$ and $Sc$ galaxies. In the remaining cases the $D/B$ value is high because of contribution from a disk-like structure having a small scale length. The bulge is dominant and the disk scale length to bulge scale length ratio ($r_s/r_e$) for these galaxies is much smaller than in lenticulars and spirals.

To better isolate these disks and other faint features in the 2-D images, we have developed a number of morphological filters. As the name suggests, these filters deal with shapes within images. The morphological gradient filter has been found to be especially useful in locating changes in the luminosity levels since it depends less on edge directionality than the Sobel operator. We describe in detail the gradient and other morphological filters.

We then discuss the detailed morphology of individual galaxies in the sample. We say a galaxy is disturbed if it possess at least one of the following. (1) A secondary nucleus (a non-stellar brightness peak within 10 kpc of the galaxy brightness peak); (2) tidal features; (3) other features that result in distorted isophotes. We look for these signs of disturbance by making use of color maps, distribution of intensity profile parameters and morphological image processing techniques. We show that radio galaxies, though they possess a morphology very similar to that of elliptical galaxies, more often exhibit signs of disturbance than normal elliptical galaxies: there is a higher incidence of secondary nuclei in radio galaxies, their isophotes deviate from being elliptical more often than for normal galaxies and there is a greater incidence of blue structures that are indicative of recent star forming activity.

We explore in some detail the connection between radio properties and features and parameters in the optical and near-IR bands. We find that FR II radio galaxies are more likely to possess a disk than FR I radio galaxies. We find that blue central regions preferentially occur in the more powerful radio
galaxies. In some of the radio galaxies, star formation is seen to preferentially lie along the radio axis and is likely to have been induced by the radio emission. Such a phenomenon has been noted before but for higher redshift radio galaxies.

We model the age of the recent star formation using synthetic spectra in the optical and near-IR bands. We assume that the galaxy is formed at some epoch in the past, with the Scalo stellar initial mass function (IMF). To such a galaxy we add a starburst, again with the Scalo IMF. The spectrum of the galaxy, at the present time, is the sum of the individual spectra of appropriately evolved stars originally formed, and in the starburst. We compare broad band colors of the spectrum with observed colors, and determine the burst mass and epoch for the best correspondence.

Finally, we provide a summary of the thesis and discuss the new lines of investigation, for studying the morphology of radio galaxies, that have been suggested by the present work.