Chapter 1

Introduction

1.1 Overview

The Magellanic Clouds provide a unique environment in which to study many interesting and astrophysically challenging problems. They are relatively nearby, have a position which makes them observable for the entire year and they provide ideal case studies to investigate many classes of sources. Although distances to both the Small and Large Magellanic Clouds are still somewhat uncertain, they are relatively well-known, allowing detailed quantitative studies to be undertaken. The Clouds have been studied over a wide range of frequencies, from low-frequency radio observations through to satellite based gamma-ray studies.

The Magellanic Clouds are one of the prime observing targets for the Molonglo Observatory Synthesis Telescope (MOST). Soon after the instrument was commissioned in 1981 an observing programme to survey both the Small and Large Magellanic Clouds was undertaken. Operating at a frequency of 843 MHz with an angular resolution of 44 arcsec, the MOST was the highest angular resolution aperture synthesis radio telescope in the southern hemisphere in regular use at that time. The resulting sub-arcminute angular resolution images provide an excellent base from which to select objects for further study. The MOST Magellanic Cloud surveys were in progress when the work reported here was started and the images from the MOST Small Magellanic Cloud survey have since been published in Turtle et al. (1998).

The MOST is a powerful imaging instrument particularly suited to radio surveys and to imaging, in a single 12-hour observation, sources with complex extended morphologies. In addition to "full synthesis" observations, an observing mode called "CUTS" can be used in which around 10 sources are each observed for a few minutes with a cadence of approximately one hour over the course of an observation. In this way a number of sources can be imaged in a single observing session, allowing a survey of a large number of sources to be undertaken in a relatively short amount of total observing time. However, the MOST is restricted to a single observing frequency, a relatively narrow continuum bandwidth of 3 MHz, fixed right-circular polarization and a fixed physical configuration.

In the early 1980s, the pressing need for a frequency agile synthesis radio telescope in the southern hemisphere was acknowledged. This need was addressed by the official opening of the Australia Telescope in 1988, with regularly scheduled observations commencing in May 1990. The Australia Telescope Compact Array (ATCA) is a sparse radio synthesis array, with 15 baselines compared to 351 for the Very Large Array (VLA) and 40 for the Westerbork Synthesis Radio Telescope (WSRT). It was envisaged that to provide good spatial frequency coverage, four separate observations in different baseline configurations would be required to adequately image a typical radio source. In practice, such usage would have precluded the use of the ATCA to survey a large number of sources. At the time, this raised questions such as:

- Was a survey of a large number of sources in a small number of observing sessions achievable?
- Would a "CUTS"-type observation with the ATCA be successful for compact sources?
- Given the small number of baselines, could the resulting images be deconvolved and used for quantitative analysis?

This thesis presents the results of an observing programme which used preliminary Magellanic Cloud survey images from the MOST to select sources to be studied with the then new ATCA. To test the viability of the "CUTS" technique for the ATCA, a single 12-hour observation at 4790 MHz was made in May 1990, targeting seven sources and two calibrators in the Small Magellanic Cloud (SMC) over 1-hour cycles. The reduced data produced images of satisfactory quality to enable quantitative analysis including the determination of peak and integrated flux densities and the angular extent of the source. The observing programme was therefore extended to include further sources in both Clouds over a 12 month period. At that time only 5 ATCA antennas were operational, giving just 10 baselines. The observing techniques outlined here were extremely fruitful, and are now the basis for many continuum observations with the ATCA, made with the full set of 6 antennas and 15 baselines.

The properties of 61 compact radio sources in the Clouds are presented in this thesis, including flux densities at frequencies from 408 MHz to 8.6 GHz, radio spectral indices, and the presence of coincident X-ray emission and likely classification of the emitting object. These studies have had significant scientific implications, including the selection of source candidates for other survey work and detailed studies of individual objects, two of which are the subjects of detailed chapters of this thesis.

1.2 A Brief History of Magellanic Cloud Surveys

The southerly location of the Magellanic Clouds made them a natural target for the developing astronomical instrumentation that was built in Australia after the Second World War. The development of radio astronomy in Australia was a notable scientific post-war success due mainly to an excess of old radio and radar equipment from the war and the presence of many talented scientists and engineers. As a consequence Australia is one of the leading countries in radio astronomy research and contributes at a level far above that which would be expected on the basis of its modest population.

Early radio and optical observations attempted to define the spatial extent of the Small and Large Magellanic Clouds, and to catalogue sources of interest such as emission nebulae and star formation regions. Henize (1956) compiled an extensive optical catalogue of emission-line stars and nebulae from Hα images of the Magellanic Clouds. The Henize catalogue is still widely used and provides an extensive atlas of sources for comparison with observations at other frequencies. Some of the earliest continuum radio observations of the Clouds were undertaken at the Fleurs field station (located in the west of Sydney) where a low-frequency cross-type telescope was developed under the leadership of B.Y. Mills. Observations were made at 85 MHz with an angular resolution of around 50 arcmin and sensitivity of about 1 Jy "under ideal conditions" (Mills 1955). These observations allowed the radio extent of the Magellanic Clouds to be compared to previously-mapped optical and 21 cm hydrogen line emission boundaries.

In the late 1950s radio astronomy instrumentation development proceeded along two parallel paths. The Commonwealth Scientific and Industrial Research Organization (CSIRO) decided to pursue radio astronomy research by concentrating on the construction and operation of the 64 m Parkes radio telescope which was completed in the early 1960s. Around the same time, the University of Sydney had attracted Mills to their staff with the primary purpose of constructing a large cross telescope operating primarily at 408 MHz. The Molonglo Cross formed 11 fan beams producing maps with angular resolution of around 3 arcmin. One of the main observational programmes of the Molonglo Cross was a survey and corresponding catalogue of bright radio sources in the southern sky, published as the Molonglo Reference Catalogue (MRC; Large et al. 1991). A number of other catalogues covering selected regions of the sky were also published, including the MC4 catalogue of sources towards the Magellanic Clouds (Clarke, Little & Mills 1976), which identified 75 sources towards the SMC and 227 sources towards the Large Magellanic Cloud (LMC). Clarke, Little & Mills (1976) divided those sources for which high-frequency or optical data were available into two categories: sources located in the Clouds and "unidentified non-thermal sources" which were presumed to be external to the Clouds.

The Parkes telescope provided frequency flexibility at centimetre wavelengths and provided the means to undertake H I spectral-line observations. In fact, Parkes observations of the Magellanic Clouds during the 1960s primarily consisted of H I spectral-line observations (see, for example, McGee & Milton 1966). Radio sources in the LMC observed with the Parkes radio telescope at 2.7 GHz and 5 GHz were catalogued by McGee, Brooks & Batchelor (1972a, 1972b). These data led to McGee & Newton (1972) classifying the sources as H II regions, possible SNRs, or steep spectrum sources that were presumably not located within the LMC. Similarly, Parkes continuum observations of the SMC at 5 and 8 GHz were published by McGee, Newton & Butler (1976) and comparisons made with published radio and optical data.

Davies, Elliott & Meaburn (1976; hereafter referred to as DEM) undertook an extensive optical survey of the nebula complexes in both the Small and Large Magellanic Clouds using the Schmidt telescope on Siding Spring mountain. In addition to the publication of the images of the photographic plates and source catalogues, they were able to utilize the radio data obtained with the Molonglo Cross and Parkes telescopes to (i) compare the optical data with the neutral hydrogen distribution; (ii) compare the optical data with the distribution of radio continuum emission in the LMC; (iii) discuss the identification of supernova remnants in the Clouds; and (iv) discuss the nature and identification of the small-diameter objects in the Clouds.

1.2.1 Supernova Remnant Surveys

Supernova remnants (SNRs) are the subject of much astronomical research. The Magellanic Clouds provide an obvious location in which to search for SNR candidates and to undertake detailed studies of individual remnants lying at relatively well-determined distances. Observations across a range of frequencies are required to identify an SNR candidate with certainty. The ability of the Parkes antenna to operate across a range of centimetre wavelengths permits the discrimination between thermal and non-thermal radio emission, and has aided in the detection of many new SNRs within the Clouds.

The detection of non-thermal radio emission from N49, N63A and N132D in the LMC by Westerlund & Mathewson (1966), and comparison of the radio and optical properties of these sources with those from known Galactic SNRs, led these three objects to be identified as SNRs from Type I supernovae (SNe). These were the first extragalactic SNRs to be discovered.

The first SNR discovered in the Small Magellanic Cloud was N19 (Mathewson & Clarke 1972), identified using a combination of radio and optical techniques during a search specifically for SNRs in the SMC. The radio data were taken from observations of the SMC with the Molonglo Cross at 408 MHz, and were compared with optical images in Hα and [S II]. The criterion for an SNR identification was that an optical emission region coincided with a radio source, and that the ratio of Hα to [S II] was less than two. This pioneered the technique of using the intensity of [S II] as a discriminator between emission from expanding SNR shells and that from radiatively-excited H II regions.

The success of the initial searches prompted more detailed and comprehensive searches, again using a combination of optical and radio techniques. Mathewson & Clarke (1973a) reported the discovery of nine new SNRs in the LMC and Mathewson & Clarke (1973b) found one additional SNR in the SMC. Thus at that time, 14 SNRs had been discovered in the Magellanic Clouds and 12 were known in the LMC, allowing limited statistical interpretation. Mathewson & Clarke (1973a) predicted that there should be some 340 SNRs in the Clouds detectable by the Molonglo Cross at 408 MHz, assuming that the integral luminosity function of SNRs in the LMC had the same shape as that for the Galactic population of remnants. However, in a detailed analysis of the Molonglo Cross 408 MHz survey of the Clouds, Clarke (1976) suggested that there were few SNRs remaining to be discovered in the Magellanic Clouds.

1.2.2 X-ray Studies

The LMC was the first external galaxy to be detected at X-ray wavelengths (Mark et al. 1969). X-rays from the SMC were first detected in 1970 using a rocket-borne instrument (Price et al. 1971). *Uhuru* satellite observations determined that this X-ray emission was from SMC X-1 (Leong et al. 1971) and identified two further transient sources in the SMC.

A detailed and more sensitive X-ray survey of the Magellanic Clouds was undertaken using the Imaging Proportional Counter (IPC) aboard the *Einstein* observatory (Long & Helfand 1979). In this (preliminary) survey of the LMC, X-ray emission was detected from 10 previously identified SNRs. Two further SNRs (N157B and N158A), which had been identified previously on the basis of their radio spectra, were also detected as strong X-ray sources.

Following the first *Einstein* observations of the LMC, Seward & Mitchell (1981; the 1E catalogue) undertook a similar survey of the SMC. They covered over 40 square degrees, and detected 26 sources of which five were identified with non-SMC objects. SMC X-1 was the only previously-known source detected in this survey. The second brightest source detected was identified as a previously-unknown SNR 1E 0102.2–7219. Four further sources were identified as being possible SNRs solely on the basis of their X-ray luminosity. Long, Helfand & Grabelsky (1981) conducted a similar soft X-ray survey of the LMC using the *Einstein* observatory imaging instruments. They detected 97 sources and identified nineteen of these with either known optical and/or radio SNRs or proposed them as SNR candidates. From follow-up *Einstein* High Resolution Imager (HRI) observations, they determined that a further six sources were also SNRs. In addition, they argued that on the basis of statistical considerations it could be expected that at least another 20–25 sources were likely to be SNRs.

1.2.3 Further Optical and Radio Observations

The early optical, radio and X-ray studies clearly showed that observations across the full wavelength range offered by the available instrumentation are needed to build up physical understanding of individual sources in the Magellanic Clouds. In particular, multi-frequency radio observations and the advent of X-ray satellites made significant contributions to advancing our knowledge about SNRs, H II regions and the environment within the Clouds.

One of the immediate consequences of the detailed *Einstein* survey was that Tuohy et al. (1982) used the Anglo-Australian Telescope (AAT) to obtain optical emission line images of four LMC SNRs first detected at X-ray wavelengths. These relatively strong X-ray sources were found to have optical spectra which are dominated by Balmer emission but with very weak emission in [O III] and [S II]. Comparisons with the optical spectra of Galactic SNRs led to the identification of these sources as the remnants of Type I supernova explosions.

Using photoelectrically calibrated maps of Hα emission, Kennicutt & Hodge (1986) measured integrated fluxes for several hundred H II regions to study the properties of

H II region populations in the Clouds. This work, along with the Henize (1956) and DEM studies, are probably the most widely used catalogues of Hα emission in the Magellanic Clouds.

One of the most comprehensive studies of supernova remnants in the Magellanic Clouds was undertaken by Mathewson et al. (1983a, 1984, 1985). Mathewson et al. (1983a) presented a catalogue of SNRs in the Magellanic Clouds together with optical, radio and *Einstein* IPC and HRI images. At that time, there were 25 confirmed remnants in the LMC and six in the SMC. These numbers were sufficiently large for some typical SNR parameters to be determined, including the conclusion that the SNR rate in the LMC was one per 275 yr, and in the SMC, one per 800 yr (with considerable uncertainty).

Inoue, Koyama & Tanaka (1983; the IKT catalogue) used the *Einstein* IPC to survey the Clouds again, with exposure times at least a factor of 10 greater than those used by Seward & Mitchell (1981). Mathewson et al. (1984) used these X-ray observations, along with narrow-band optical imaging and 843 MHz radio observations, to identify a further two SNRs in the LMC and five SNRs in the SMC, bringing the total number of known SNRs to 27 in the LMC and 11 in the SMC.

At around the same time, Mills et al. (1984) reported on high resolution radio observations undertaken using the MOST at 843 MHz. These observations confirmed six of eighteen SNR candidates in the SMC. Two of the six had no apparent X-ray counterpart, possibly due to their location near the edge of the X-ray fields where the detector sensitivity is relatively low. MOST observations of the LMC revealed a number of relatively large-diameter radio sources with the characteristic ring morphology of SNRs. Mathewson et al. (1985) undertook narrow-band optical imaging of these candidates and, by comparing these data with X-ray and radio images of the same fields, determined that four of the candidates were indeed SNRs. A further source was thought to be a "superbubble" resulting from one or more supernovae. This work brought the total number of SNRs in the LMC with optical identifications to 32.

1.3 This Work and Contemporaneous Studies

The MOST 843 MHz survey of the Magellanic Clouds began in the mid-1980s, with the observations primarily done in late Winter and early Spring when the Clouds transit near midnight. Whilst not essential, it was found that telescope systems were more stable at night and image degradation due to solar interference was minimized. Fields for which the image quality was poor, due to instrumental or environmental factors, were subsequently reobserved. The MOST "raw" images, which are available shortly after the conclusion of each synthesis observation, are of sufficiently high quality to enable immediate astrophysical interpretation. These preliminary images were used to select the source sample for the study that is presented in this thesis.

The launch of the Infrared Astronomical Satellite (IRAS) in January 1983 allowed the Magellanic Clouds to be surveyed in another wavelength band. The resulting images and catalogue of infrared sources in the SMC and the LMC are presented in

Schwering (1989a) and Schwering (1989b), respectively. They found that, in general, there was a good correlation between infrared emission and the distribution of H II regions and dark clouds.

Bruhweiler et al. (1987; the BKGS catalogue) followed up the deep X-ray imaging undertaken by Inoue, Koyama & Tanaka (1983) using long *Einstein* IPC exposures covering about 50% of the main bar and wing of the SMC. They detected twelve new sources and discussed the possibility that two or three may be SNRs. Four sources which had marginal detections in the catalogue of Bruhweiler et al. (1987) were selected as targets for the SMC sample presented in this study. Based on a re-analysis of the *Einstein* data, X-ray catalogues of the SMC are presented in Wang & Wu (1992) and of the LMC in Wang et al. (1991). A more recent *ROSAT* X-ray survey of the Magellanic Clouds offers higher angular resolution and sensitivity; the results for the SMC have been published in Kahabka et al. (1999) and in Sasaki, Haberl & Pietsch (2000) for the LMC.

During the 1980s, as observing and data reduction techniques improved, a joint Australian-German observing programme was initiated at Parkes to obtain multi-frequency images of the Magellanic Clouds at centimetre wavelengths. In addition, polarimetry data were also obtained. A detailed analysis of this Parkes multi-frequency data has been reported in a series of papers (Filipovic et al. 1998c, and references therein). Later papers in this series present source catalogues and compare the Parkes radio data with data from previously-published optical, infrared, radio and X-ray surveys. The MOST and ATCA 5 GHz data presented in this thesis are compared extensively with the results of these most recent Parkes surveys.

The Australia Telescope enabled the first sub-arcminute, interferometric studies of H I absorption in the southern sky. Such absorption line studies are far more efficient if preceeded by the identification of strong, compact continuum sources at 1.4 GHz. The SMC and LMC samples presented in this thesis provided the highest angular resolution continuum observations available from which to select candidates for H I absorption studies. These samples were therefore used to select the bulk of the target sources for the first such study of absorption in the direction of the LMC by Dickey et al. (1994).

1.4 Thesis Outline

An overview of the instrumentation and data reduction techniques used in synthesis imaging is presented in Chapter 2, highlighting the complementarity of the MOST and the ATCA. Details of MOST and ATCA observations of the Small and Large Magellanic Cloud sources are given in Chapter 3.

MOST and ATCA images of each source in the SMC are presented in Chapter 4. The morphologies, flux density and radio spectrum of each source as revealed by previous work and the current studies are discussed, as is its likely classification as a background source, H II region or supernova remnant. These studies highlight some of the issues associated with the reliable classification of sources, particularly when the only metric is a radio spectral index determined from limited data. Computing a spectral index without careful consideration of the source structure, and how this structure changes as a function of frequency and angular resolution, often leads to an incorrect classification.

The experience gained from the analysis and source classification of the SMC sample allowed a more formal source classification method to be developed and applied to the LMC sample. Termed a "decision tree", the approach taken is to use low-frequency radio data to obtain an indicative spectrum for comparison with higher frequency ATCA and previously-published Parkes survey data. This methodology is presented in Chapter 5 along with the catalogue of the LMC source sample.

The known supernova remnant 1E 0102.2–7219 was one of the sources targeted in the initial observing programme. It appeared to be only slightly extended at the resolution of the MOST. Preliminary ATCA observations at 4790 MHz revealed an intriguing radio morphology and these results have been published in Amy & Ball (1993). These observations motivated a multi-frequency, multi-configuration ATCA campaign in 1992 in which this SNR was studied at 1.4, 2.3, 4.8 and 8.6 GHz. The results of these studies, together with detailed comparisons with optical and X-ray observations, are presented in Chapter 6. These studies have prompted recent very high profile X-ray studies of this object with the *Chandra X-ray Observatory*.

The SMC supernova remnant 0101–7226 was not included in the initial SMC sample discussed in Chapter 4 but had been identified as an SNR on the basis of X-ray data and subsequent optical and radio observations. However, later studies suggested that the X-ray source was not associated with the nearby radio emission. An SNR without X-ray emission is somewhat unusual, and this prompted further radio observations with the ATCA and observations with the *ROSAT* HRI. This work was published in Ye et al. (1995) which is reproduced in Chapter 7. It is relevant to the classification of sources discussed in Chapters 4 and 5 because our work confirmed that this source appears to be an exception to the usual rules used for classifying a source as a possible SNR.

Prospects for future work arising from the observations and analysis reported in this thesis are discussed in Chapter 8.