Chapter 8

Conclusions

This dissertation presented the work done towards low frequency study of a sample of new candidate Galactic Supernova remnants (SNRs). Details of the observations of this sample of new candidate SNRs, data calibration, analysis and interpretation were presented. A number of other sources are visible in the $\sim 1^\circ.4$ field of view of these observations, and the nature of some of these sources was also discussed. This work constitutes one of the first observations using the imaging capabilities of the Giant Meterwave Radio Telescope (GMRT), which is predominantly a low frequency instrument. The GMRT has only recently come to a stage where it can be used for mapping complicated fields like the ones studied in this dissertation. This required system debugging, system parameter measurements, calibration and understanding of the instrument, which in-turn led to the development of data analysis techniques and algorithms and related software. Details of instrumental calibration, debugging, related software and algorithm development were also presented. A new method for the computation of polarization leakage using *only* the *co-polar* visibilites was also described. Polarization leakage manifest themselves as closure errors in the *co-polar* visibilities and this method can be used to correct for such closure errors.

8.1 Using the Giant Meterwave Radio Telescope

The GMRT was in a state of being debugged and the hardware as well as the software was unstable during the course of this dissertation. Consequently, a large fraction of time was spent in understanding the system, debugging the hardware and software and in making astronomical observations for instrumental calibration and measurement of various system parameters.

8.1.1 Testing and debugging

Measurement of the antenna locations to an accuracy of a fraction of the wavelength (baseline calibration) as well as the measurement of the fixed delays suffered by the signals from various antennas is necessary for imaging with an aperture synthesis telescope like the GMRT. These measurements were made during the course of this work. The surveyed positions of the antennas, which were in error by > 1 m, were used to bootstrap the baseline calibration process. Visibility phase variation at 327 MHz as a function of Hour angle was used to improve upon these values to an accuracy of ~ 20 cm. Later, using 1420 MHz observations, in combination with the GPS measurements, antenna positions to an inferred accuracy of ~ 5 cm were measured. Antenna fixed delays were measured from the phase gradient across the band. Using the measured antenna positions and antenna fixed delays, software was written for off-line fringe stopping. This software was extensively used with the prototype 8-antenna correlator, which did not have the facility for fringe stopping, as well as during the early stages of the full 30-antenna correlator. Measurement of flux densities tied to standard flux scales also requires measurement of other system parameters like the primary beam attenuation, system temperature, etc. All these measurements were also made.

The digital FX type correlator of the GMRT was used for these observations for system calibration and later for scientific observations. In the early stages of the commissioning of the telescope and the correlator, data was corrupted due to problems in the hardware (servo, telemetry, antenna tracking, Local oscillators systems, etc.) as well as the software (on-line control, data acquisition system, fringe stopping and correlator control, data acquisition systems, etc.). Various tests/simulations were done to gain understanding of the working of the telescope/correlator. Several test observations were also done to identify problems and potential sources of data corruption – particularly in the correlator hardware (which often resulted in high closure errors in the data) and fringe stopping software.

8.1.2 Software development

It was clear that in these early stages of this new instrument, monitoring the data quality and the health of the system during observations was of paramount importance. Since there were many sources of data corruption and the manner in which they affect the data were varied, it was useful to develop techniques and software which can automatically identify as many of these problems, as early on in the data analysis process as possible.

Extensive software was developed for this purpose in the form of general purpose object oriented libraries, as well as in the form of programs for on-line and off-line data processing and display. In order to make application programs usable by others, a system of user interface and documentation was also developed. This software system now runs into $> 50,000$ lines of `C`, `C++` and `FORTRAN` code.

The complex visibility function, V, depends on a number of telescope parameters like the system temperature, sensitivity, antenna fixed delays, antenna positions, etc. Since the complex visibilities are a function of a multitude of parameters, and different debugging purposes require viewing V with respect to various quantities, a compact macro language was developed using which, data can be extracted from the GMRT visibility database. This was implemented in the form of a stand alone library as well as used in the application program named `xtract`. The content and the output format can be easily specified via this macro language, allowing easy access to astronomical/engineering data. This also allows easy interface to existing data display software for visualization. This was used extensively during the course of this work and is now being widely used for a variety of measurements like the system temperature, antenna sensitivity, antenna beam shapes, etc.

Equations for solving for antenna based complex gains using the complex visibility measurements for an unresolved source were derived using complex calculus. This led to a simple interpretation of the algorithm to solve for the antenna gains, which in turn led to the development of an algorithm which is robust in the presence of often large amounts of severely corrupted/bad data. This was done by (1) doing two passes to eliminate dead/bad antennas, (2) automatically eliminating out-lying points using robust averaging (where the mean value is computed by iteratively eliminating points which deviate from the mean by greater than a threshold value). This algorithm was also used to identify and flag corrupted data in a semi-automatic fashion. This algorithm, implemented in the program `rantsol`, was also extensively used and is now used by others for various measurements and for the phased array mode of operation of the GMRT (Sirothia 2000). It was also used for on-line data monitoring and for the semi-automatic identification of bad data. The output of this program was examined by another program (`badbase`) which identified consistently bad antennas and baselines in the data. This information was later used to flag data before using it for mapping. Data with high closure errors was often present on a few baselines out of a total of 435 baselines. The calibration program of `AIPS` is very sensitive to such bad data and the presence of about 10% bad baselines could result into poor solutions or sometimes no convergence at all. Automatic identification of such bad data was therefore important and a great time saver.

Signals from the two orthogonally polarized feeds can leak into each other at various point in the signal path. The planned Walsh switching of the signals from the two orthogonal feeds to minimized cross-talk has not yet been implemented for the GMRT. Besides, Walsh switching will not eliminate any leakage introduced before the switching point. Such leakage can result into closure errors even in the *co-polar* visibilities. This has been pointed out earlier by Rogers (1983) in the context of VLBA. A more detailed study of this was done by Massi et al. (1997) for European VLBI Network (EVN). Polarization leakage at a few percent level at most bands and at a much higher level at 150 MHz have been measured for the GMRT. The current GMRT correlator measures only the *co-polar* visibilities. A method was therefore developed to solve for the polarization leakage using *only* the *co-polar* visibilites for an unpolarized calibrator. The solutions, though have 3-parameter ambiguity (in the same sense as the phase ambiguity in Self-cal solutions), can be used to study the polarization properties of the individual antennas as well as to correct for the closure errors arising due to polarization leakage.

Other software developed during the course of this work includes software for time and bandpass calibration, data display, checking the consistency of the visibility database, fixing/editing data affected by problems in the system hardware/software, off-line correction of visibility phase due to antenna position offset/frequency offset, etc.

8.2 Candidate Galactic SNRs

The GMRT was finally used at 327-MHz to map a sample of seven fields selected from the surveys by Gray (1994a) and Duncan et al. (1997b) containing candidate SNRs. Most of these SNRs are large in size and their morphology is easily discernible at resolution of about an arcmin. These observations constitute the most sensitive, highest resolution observations for these and other sources which happen to be within the field of view. Partly due to system problems and ionospheric phase corruption, and partly due to the well known problem of deconvolution of extended sources, these extended sources tend to break up at higher resolution. Higher resolution images were therefore made and used only for small angular size objects.

Some of these objects are already listed in the SNR catalogue (Green 2000) based *only* on the morphological evidence from single high frequency observations. These GMRT observations establish the non-thermal nature of the emission and typical SNR morphology for six of these candidate SNRs and confirms them as Galactic SNRs. G001.4−0.0 is detected as a clear partial arc of emission, coincident with a faint arc of emission seen in the OH (1720 MHz) emission (Yusef-Zadeh et al. 1999). An OH (1720 MHz) spot has also been previously detected towards this direction and coincides with the arc seen in the radio continuum (Yusef-Zadeh et al. 1999). Recently it has been argued that the OH (1720 MHz) emission is a good tracer of the interaction between the shock front driven by the SNR blast wave and molecular clouds (Frail et al. 1994). The OH (1720 MHz) maser emission is distinguished from the OH maser emission at 1665, 1667 and 1612 MHz by the former being positionally and kinematically associated with SNRs while the later is associated with HII regions. OH (1720 MHz) emission associated with SNRs is believed to be due to the blast wave driving a shock in a denser molecular cloud. OH masers at 1665, 1667 and 1612 MHz cannot be produced under the same physical conditions and the absence of these lines in observations which detect the OH (1720 MHz) line favors this interpretation. The morphology of G001.4−0.0 in OH (1720 MHz) emission and radio continuum suggests that the arc of emission corresponds to the shock front. Absence of emission on the eastern side may be explained by the absence of such a cloud on that side. G003.8+0.3 is clearly visible as an incomplete arc of emission, embedded within a ring of thermal emission seen in the IRAS 60μm image. Its morphology is also clearly deciphered in the radio continuum image from the 11 cm 100-m Effelsberg survey (Reich et al. 1990). G004.8+6.2 is seen as an almost complete shell of emission just east of the shell-type Kepler's SNR. This SNR is also present in the field of view of a VLA observation and is also detected, although at a very low level, in the NVSS image of this region. The morphology and the measured integrated flux from the GMRT and VLA observations are in good agreement. G356.2+4.5 is a faint partial shell. This SNR is also visible in the NVSS image of this region, but the images at 327 and 1400 MHz suffer from the problem of missing flux, which did not allow the determination of the spectral index. However, the morphology is strongly in favor of this being an SNR. G356.3−1.5 is a barrel shaped SNR. The 834-MHz image of this source was severely affected by the grating response of a nearby strong source. However, the barrel morphology, with significant emission projected between the two rims, is clearly seen in the 327-MHz image. G004.2−0.0 is detected as an unresolved source. The spectra measured between 327 and 843 MHz for this source is consistent with it being a flat spectrum source. Presence of significant thermal emission in the IRAS 60μm image, however, suggests that this may not be an SNR but a flat spectrum thermal source.

8.3 Other sources in the fields

The $\sim$ $1^\circ.4$ beam of the GMRT at 327 MHz reveal a number of other compact, moderately resolved and as well as well resolved sources. The 1 arcmin shell type source G003.6−0.11, well resolved in the high resolution GMRT image, coincides with significant thermal emission and a H II region. A shell of emission, with three compact source superimposed is clearly visible. Resolved images of this source at 1.4 and 5 GHz were also made using older VLA observations by Gaensler (1999) and Yusef-Zadeh (data obtained from VLA achieves) respectively. Emission from the shell appears to be non-thermal while one of the compact sources is consistent with it being a symbiotic star (Seaquist & Taylor 1990). H I absorption observations towards this direction indicate that one of the compact sources and the shell are at similar distances while another compact source is a background object. Earlier, RRL emission has also been detected from this direction at $\sim$ 5 GHz, but at a resolution which covers the entire source. Higher resolution continuum and RRL observations with the VLA are required to determine the true nature of this object.

Maps of the field containing G004.2−0.0 and G356.3−1.5 reveal extended emission, coincident with previously classified UC H II regions. Recently, such extended emission has been detected around a number of UC H II regions using the VLA in D-array configuration (Kurtz et al. 1999; Kim & Koo 2001). This extended component was not detected earlier since earlier observations were done in the B- or A-array configurations at high frequencies which were insensitive to large scale emission. The GMRT offers a unique advantage in imaging such sources in terms of providing high resolution *and* simultaneous sensitivity to emission at large scales. Such extended emission, if associated with the UC H II regions, can mitigate the “age problem” for these objects (de Pree et al. 1995, and reference therein).

A linear structure, seen in the field G356.3−1.5, is similar to other linear structures in few other observations in the Galaxy (Gray 1996). Higher resolution imaging of this feature is required to determine its physical properties.

8.4 Future directions

This work demonstrated and extensively used the imaging capabilities of the GMRT at low frequencies. The GMRT provides high resolution along with sensitivity to relatively large angular scales (~ 25 arcmin) - both of which are of crucial importance when mapping complex fields like the Galactic plane. All maps reveal a rich variety of objects in the field. For many of them, these observations constitute the first low frequency observations and reveal features not known from higher frequency observations. Sensitive high resolution observations in the Galactic plane with the GMRT is therefore expected to give rich scientific dividends. Spectral information is often a crucial ingredient for understanding the physical properties of these objects. As a future, possibly Observatory Project, a high resolution multi frequency survey of the Galactic plane with the GMRT will be of great interest.

It is clear that the role of magnetic field is as important as the kinetic energy of the relativistic electrons in explaining the emission from typical SNR. Measurements of the magnitude of the magnetic field for some of the SNRs reveal magnetic field amplification of the ambient by $2-3$ orders of magnitude. However these observations are few and far-in-between (e.g. Claussen et al. 1997; Brogan et al. 2000). High resolution images of many SNRs reveal compact sources embedded in the diffused larger scale emission from the SNR. If these objects are background sources, rotation measure (RM) measurements against these sources can provide a measure of the magnetic field for a larger sample of SNRs, which will be valuable input to the theoretical models to explain the magnetic field amplification.

Distances to many Galactic SNRs are poorly determined. Errors of a factor of 2 or more are frequently found in the quoted distance (often using the Σ-D relation (Case & Bhattacharya 1998, and references therein)). Distance estimated using the velocity structure of H I absorption profiles towards SNRs in combination with the Galactic rotation model, often provides a more reliable distance estimates. Such observations with the GMRT to determine the distance to a large sample of SNRs will be very desirable.

The 327 MHz images of the UC H II regions in the field of view of some of the images presented here reveal, somewhat unexpectedly, reasonably extended and strong emission around the compact cores. Such extended emission has also been recently detected at higher frequencies using the VLA (Kurtz et al. 1999; Kim & Koo 2001). The exact nature and the mechanism that could sustain such large scale (few pc) emission is far from clear. The GMRT images are the first low frequency images of these objects at resolutions comparable to those at higher frequencies. Such observations of a sample of UC H II, preferably at 327, 610 and possibly at 1420 MHz, which are readily doable with the GMRT in its present state, are highly desirable and will almost certainly pay rich scientific dividends in this field. In particular, the proposed model to explain the extended emission till low frequencies (see Chapter 6 and Kim & Koo (2001)) appears to have "preferred arrangement" where a massive star is formed off-centre from a hot core which is in-turn embedded in a lower density molecular cloud. If a large fraction of UC H II do show extended emission, a more refined model may be required which can relax the requirement of this preferred arrangement of the components.

Measurement of the low frequency turn-over below 100 MHz, due to free-free absorption by the wide spread extended low density warm ionized medium (ELDWIM) in the Galaxy, provides information about the continuum optical depth towards various lines of sight in the Galaxy. The path lengths and filling factors derived from the low frequency radio recombination lines (RRL), detected in almost every direction in the inner Galaxy (Roshi & Anantharamaiah 2000), suggests that the gas may be the extended low density HII envelopes surrounding higher density HII regions (Anantharamaiah 1985b, 1986). Also, the parameters of this gas, derived from RRL observations and the low frequency turn-over in the SNR spectra, are very similar, suggesting that the same gas is responsible for the RRL emission and the low frequency turn-over in SNR continuum spectra. If we assume that the properties of the ionized gas derived from these observations is typical, then we can expect to detect RRLs through stimulated emission due to the background radiation of SNRs at 330 and 1420 MHz. Such a detection will directly give the (negative) line optical depths at the two frequencies. High resolution RRL and continuum observations at low frequencies towards extended but strong SNRs will make tremendous advance in this area. All previous studies either had poor sensitivity or poor resolution (or both!) making it impossible to connect the absorption or RRL emission to known thermal sources. The GMRT and the VLA provides the required resolution at 327, 610 and 1420 MHz and are sensitive enough for these observations.

8.5 Some thoughts on the role of software for the GMRT

Mapping at low frequencies is inherently a more compute intensive job. The algorithms for eliminating the distortions due to large field of view require substantially higher computing. The yet to be developed technique for phase calibration in the presence of nonisoplanatic ionosphere is bound to further increase the requirement on computing power. These computational challenge can be handled by parallelizing the imaging and phase calibration algorithms. This can be done either on a dedicated high performance computers (work on this is already in progress in `AIPS++`) or by using a network of standalone, reasonably fast computers connected via fast data link (distributed computing). The advantage in the second approach is that it will be accessible to a larger community at a relatively cheaper price.

Deconvolution errors in the presence of extended emission, abundantly present in the Galactic plane, will be significant (Briggs 1995). Apart from generating algorithm related artifacts, the residuals are also correlated with the sources in the field indicating systematic errors in the model image (or equivalently, deconvolved image). One of the important pieces of information, not used in the deconvolution algorithms is that the extended emission has finite correlation length, which can vary across the image. Any algorithm which uses this information is likely to perform much better in terms of image fidelity. Also, most iterative deconvolution algorithms stop the iterations when the brightest component is comparable to the expected thermal noise. This stopping criterion is good for compact emission. However, for extended emission, this leaves correlated flux which is within the estimated noise level.

Field of view and the scale of radio emission at low frequencies is relatively large. Conventional deconvolution algorithms (CLEAN or MEM based), which treat each pixel in the image as an independent degree of freedom (zero correlation length), produce the well known instabilities and ”breaking up” of extended emission. A generalization of the MEM and multi-scale deconvolution algorithms using a pixel model with a finite correlation length (Pixon), would drastically reduce the number of degrees of freedom required to represent the image (Pina & Puetter 1993; Puetter & Pina 1994). Development of algorithms for the deconvolution of images made using radio interferometric telescopes is a very interesting and useful future direction of research in this field.

Mapping at low frequencies is relatively more difficult and a time consuming task. This is due to a combination of larger number of sources of data corruption and inherent difficulties in mapping at low frequencies (see Chapter 4). Refining the techniques and methodology for data calibration and analysis described in this dissertation, with the ultimate goal of developing techniques for automatic data flagging, is an interesting future direction of research, particularly in the context of low frequency instruments like the GMRT and the future instruments like the Low Frequency Array (LOFAR) and

Square Kilometre Array (SKA). Software developed during the course of this work produces information about corrupted data, at least for the calibrator scans. Development of supporting software to automatically identify systematic patters (like consistently bad baselines/channels) and transform this information into flagging tables directly readable by mapping software is highly desirable. Similarly, development of software to generate on-line flagging information based on the information of the health of various systems is required to improve the data quality. Combination of these automatic on-line and off-line flagging information will go a long way in improving the data quality and reduce the time it takes to map with such data. Work on these lines will be almost *necessary* for large scale mapping projects like multi-frequency surveys of the Galactic plane.

The software for on-line control of the telescope and the electronics is complex, requiring a large number of settings to be done for a typical observation. Complexity of this software for the GMRT at present is directly visible to the end user - something which is neither desirable nor necessary. Design and development of a integrated interface, which presents an astronomically useful view of the instrument (antenna pointing, tracking, frequency/bandwidth selection, observing schedule, etc.) will go a long way in making it easier to use the instrument as well as reduce possibility of human errors during observations.

Online data display for the GMRT is as good as missing. The data acquisition software as well as the on-line telescope control software, however, provides enough hooks from where the relevant information can be tapped and displayed online for a much improved monitoring of the system as well as the data. This again requires an integrated system of software, which can perform some on-line data processing and display. The former (on-line data processing software), to a large extent, was developed during the course of this work and is currently usable. Development of the latter (display software) is still in infancy and requires further work.

All the research and development suggested above, which ultimately also requires non-trivial software development, must be done in a well thought out manner. This usually requires participation of a number of people with varied interests and skills and at different points of time. A carefully thought-out underlying software design, for long term use and development of the software, is therefore necessary. In my opinion, a patchy ad hoc development of potentially unrelated stand-alone software, developed by people with different skills and style of coding (possibly based on old software technology and design techniques), at different times, is unlikely to be useful in the long run and will be a waste of enormous human and computing resources. Observational astronomy and related instruments have moved into a regime which is dominated by use of complex software which is not always hidden from the end user (particularly when directly using complex instruments like the GMRT). In the context of computer language design, it is said, "*The connection between the language in which we think/program and the problems and solutions we can imagine is very close. For this reason restricting language features with the intent of eliminating programmer errors is at best dangerous*"[1]. Similarly, I reckon, the connection between the problems and solutions astronomers can imagine, is closely related to their perception of the capabilities of the available data analysis software. Challenging new observations, almost by definition, require new capabilities in data analysis software and instrumentation. Aspiring and practicing observational astronomers, who like this kind of research, will therefore gain from learning new software design and development techniques. In my experience, these are not fancy tools which can be dispensed with, but actually result into stable, easy to modify and debug, and hence reliable software which in the long run, is a big time saver as well. Fluency in using/developing/modifying software gives the freedom of thought in research, which is of paramount importance in forging new areas of research – and going where few (or none) have gone before.

[1] Bjarne Stroustrup, designer of the `C++` language