Radio Study of Galactic Supernova Remnants and the Interstellar Medium

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by

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Acknowledgments

It has been a long trek - at least longer than what I imagined it would be. On the trek, I am fortunate to have come in touch with a variety of people. Some of them have become close at a personal level too. This is an attempt to convey to the reader, my appreciation for these people who directly or indirectly affected the course of this trek.

Apart from the usual stuff, I was taught by Prof. H. S. Mani, at IIT Kanpur, that ”research is not just another profession, it is a way of life”. I also remember Prof. A.P.Shukla who, in his inimitable way, sparked in his students a desire for learning. I owe my presence in the National Centre for Radio Astrophysics (NCRA) to Prof. Mani, and to Prof. Shukla for making learning interesting, and motivating me into the pursuit of research. I express my deep respectful thanks to them.

Once at NCRA, stepping into that ”way of life”, the fascination of thinking big while keeping one's feet firmly on ground came with Prof. Govind Swarup, and others at the NCRA. Prof. Swarup's description, sometimes past midnight, of the design of some mechanical structure (which, I later realized was the GMRT antenna), how to do quick arithmetic (where I was made to play the role akin to that of temporary register of a computer CPU), his introducing me to Fourier Transforms, Aperture Synthesis, and Radio Astronomy in general are the first few steps into that ”way of life” I fondly remember. His later demand that I be able to give quick answers to questions that he ”might throw at me while passing by in the corridors” helped me in many ways. His enthusiasm is even now a source of inspiration. Over the years I have interacted with him a lot. He became the source of guidance, consultations and advice and sometimes even a sink for my outbursts due to problems in personal and professional life. I am all the more thankful to him for this, and hope to continue this relationship in future.

For my thesis, I slowly gravitated towards A. Pramesh Rao probably because of his approach to work and his style of thinking and his scientific interests. He gradually became my unofficial guide at NCRA. During the early stages of the GMRT (and to some extent even now), I learnt from him the tricks of the trade, and thoroughly enjoyed that phase of my thesis and GMRT debugging and I am very thankful to him for that. All along he encouraged me to be independent. Partly because of this, I was able to do large parts of my work independently. Even for work where he was not directly involved or interested, he was and continues to remain an excellent person to bounce off ideas - and sometimes even receive healthy criticism with equanimity.

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I always had, and to some extent still have, faith in the basic goodness of all humans and in the beauty of human relationships. During this trek, I came close to some people whose approach to life and relationships however leaves a nagging doubts in the mind. I am sure that what nature does to us must be handled with care, humility, compassion and love - but sometimes people, even in normal circumstances, can become completely

insensitive and prefer going for easier solutions in life. I do not know if some of such people have contributed towards this work - positively or negatively. But I will remember them all - some of them even fondly - for a long time.

I am truly amazed by the patience and determination to constantly show the brighter side of life that my family, particularly my parents showed. Past few years have by far been the roughest patch in life I have walked and I have no doubt that without their patience and faith in me, I would have gone down that slippery path which I had begun to walk. There was nothing to look forward on that path, certainly not a thesis. I dedicate my thesis to them and I hope I have made them happier.

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The NASA's Astrophysics Data System was extensively used during the course of this work for locating data, other references available on the web and for building the bibliography database for this thesis.

Most of the work which required computers was done using computers running the GNU/Linux operating system. The software I used was almost entirely from the Open Source movement and I am convinced that without the excellent work of all those GNUians out there, my life would have been more difficult. I wish to thank all those anonymous contributors to the Open Source movement and hope to become part of it by contributing something substantial someday.

Declaration

CERTIFIED that the work incorporated in this thesis entitled "**Study of Galactic Supernova Remnants and Interstellar Medium at low frequencies**" submitted by **Sanjay Bhatnagar** was carried out by the candidate under my supervision. Such material as has been obtained from other sources has been duly acknowledged in the thesis.

Place : Pune	Prof. D. J. Saikia
XXXXXX , 2001	Thesis Supervisor

Abstract

This dissertation presents a study of Galactic Supernova Remnants (SNRs), using the newly available Giant Metrewave Radio Telescope (GMRT) at a frequency of 327 MHz. Extensive debugging and calibration of the telescope parameters was required before the above could be carried out; this is also presented here.

Towards the end of their evolution, stars with masses greater than about $8M_\odot$ explode, producing one of the most energetic observable events in the Galaxy. These explosions of massive stars are referred to as Supernovae (SNe). The shock wave traveling outwards, initially interacts with the circumstellar material of the progenitor star, giving the initial radiation detected in the x-ray, optical and radio bands. After crossing the circumstellar envelope, it continues to interact with the interstellar medium (ISM), sweeping up ISM material, and producing objects with extended emission; these are identified as Supernova Remnants (SNRs). When the mass of material swept up by this expanding blast wave becomes much greater than the ejected mass and the age of the SNR is comparable to the radiative cooling time, the shock wave decelerates, increasing the compression ratios by a large amount and setting up instabilities. Re-accelerated electrons in a thin shell, moving in the presence of a compressed (and hence amplified) magnetic field, produce non-thermal (synchrotron) radiation with a negative spectral index α ($S \propto \nu^\alpha$) which can be detected for up to $\sim$ few $\times 10^4$ years.

The circumstellar environment of the progenitor star and the properties of the local ISM produce varied SNR morphologies. Morphological studies of a large number of SNRs have allowed their classification into various categories essentially based on the radio morphology. About 80% of the known SNRs show a shell-type morphology. Other morphologies include flat spectrum filled-center (or 'crab-like'), composite, barrel-shaped, and bi-annular.

Galactic objects have usually been identified as candidate SNRs based on morphological evidence and the lack of thermal emission (excess over the expected synchrotron

emission at high frequencies). Extended emission with no associated thermal component, and showing one of the typical SNR morphologies, would be considered to be a good candidate SNR. However, reliable deciphering of the morphology requires observations with angular resolution several times higher than the extent of the emission. Further, morphological evidence alone is often insufficient for an unambiguous identification of Galactic objects as SNRs. Detection of a negative spectral index, which indicates the presence of non-thermal emission, is also used in combination with morphological evidence to identify SNRs. This, of course, requires multi-frequency observations, especially at low frequencies, to provide clear evidence of the presence or absence of an SNR. Morphology and non-thermal emission are thus the primary signatures used for the identification of SNRs in the galaxy.

Apart from providing the crucial primary morphological signature for the identification of SNRs, high resolution observations of such objects also provide valuable information about the ISM. Morphology of a given class of SNRs is believed to be the result of a similar circumstellar and ISM environment. Detailed morphological studies of SNRs therefore provide information about the local ISM and the progenitor star. With SNRs distributed all over the Galaxy, such studies provide information about the large scale distribution and structure of the ISM. Angular resolutions better than ~ 1 arcmin are often necessary to decipher the morphology of typical SNRs and a spatially separate SNRs from other sources of extended emission in the Galaxy, as well as to study their interaction with the ISM, .

Measurements of continuum radio spectra also provide other valuable information about SNRs. The shape of the continuum spectrum (and the spectral index) is also an indirect measure of the spectrum of relativistic electron energies. Simple Fermi shock acceleration theory predicts a spectral index of -0.5. While this is consistent with the spectral indices of many shell-type SNRs, substantially higher values of the spectral index have also been seen in a few SNRs (it should be noted that reliable measurements of spectral index exist only for a small number of SNRs). Models invoking self-consistent non-linear shock models of first-order Fermi acceleration can account for higher values of spectral index, but require reliable determination of the shape of the spectrum, particularly at low radio frequencies. However, for about 35% of the SNRs in current SNR catalogues, the spectral index is poorly determined or, in some cases, completely unknown. The quality of the low frequency observations in the past has also been poor due to the lower resolutions and sensitivities of various low frequency telescopes up to the present time.

To meet the dual requirements of high resolution and sensitivity for extended non-thermal emission, many Galactic plane observations have, till recently, been done using single dish telescopes at $2 - 5$ GHz with a resolution of $2 - 4$ arcmin. However, at a resolution of a several arcmin, these observations are insufficient for detailed morphological studies of the SNRs. Single dish observations at these high frequencies also suffer from the problem of confusing extended thermal emission, abundantly present in the Galaxy. High resolution observations of SNRs at a number of frequencies below ~ 1 GHz, to reliably determine the spectrum and morphology, are therefore crucial for correct identification and morphological studies, as well as for studies of the effects of the interaction with the ISM and radiation mechanism in the SNR shells.

This dissertation contains work done towards a low frequency study of Galactic SNRs using the GMRT at a frequency of 327 MHz. The sensitivity of the GMRT to large angular scales with high resolution offers a crucial advantage in mapping the Galactic plane where the emission field is usually very complex. These features of the GMRT were exploited to study a sample of nine fields containing new candidate Galactic SNRs in the southern part of the Galactic plane at 327 MHz. This sample of fields was chosen from recent surveys done using the Molonglo Synthesis Telescope (MOST) at 843 MHz and the Parkes 64-m dish at 2.4 GHz (note that the two surveys had no overlapping fields of view). The RMS noise of these survey observations was typically ~ 20 mJy/beam. Further, many of these fields are in complicated regions with strong extended emission from other sources. Substantial thermal emission at these high frequencies as well as confusing emission from nearby strong sources severely limited the image fidelity. Finally, with information available only at single frequencies for most of the objects in this sample, their identification has remained inconclusive until the present work.

Full synthesis GMRT observations were carried out at 327 MHz for this sample of fields. These observations constitute the most sensitive and highest resolution images of these fields. Our observations confirmed most of these candidates as SNRs. Six fields show well resolved shell-type and two fields show barrel-shaped objects with non-thermal emission. IRAS 60–μm images of all these fields were also examined to look for any associated thermal emission. In one of the fields designated as $\mathrm{G}004.2 + 0.0$, significant thermal emission was detected. Radio flux density at 327 MHz is consistent with a flat spectrum source suggesting that it may be a compact thermal source.

Apart from the target SNRs in the fields, images of all the nine fields provide useful

information about many other objects in the field of view. The 327 MHz images, each with a field of view of $\sim 1.4^\circ$, reveal a number of compact as well as extended sources of emission. Flux densities of the compact sources were measured at 327 MHz from the GMRT images and at 1420 MHz from the literature. The extended emission in one of the fields coincides with the location of previously identified as Ultra Compact HII (UC H II) regions. Recently, extended emission has been detected around many UC H II and the extended emission seen in this image may have the same origin. However, the true nature of the extended emission and the mechanism to sustain extended emission at such large scales to such low frequencies is not yet well understood. Similarly, the linear structure seen in another field is not clear. Such linear structures have been reported earlier as well. High resolution observations at other frequencies will be necessary for further study and to determine the nature of such objects.

Another compact source, G$003.6 - 0.1$, classified as an HII region from earlier higher frequency observations, showed significant structure and emission at 327 MHz. The GMRT observations reveal a shell-type morphology. Images at 5 GHz (from data acquired from the VLA archives) and 1.4 GHz (from the literature), at comparable resolution, provide resolved images of this object at these frequencies; two compact sources can be identified in these images, with extended emission around them. The spectrum of the extended emission is found to be non-thermal while emission from a strong compact source in the region shows a thermal signature. The current data on these components suggest that one of the components may be a radio star with a spectral index of ~ 0.5. The cometary morphology of the extended emission is similar to that seen in high resolution images of a number of UC H IIregions.

HI absorption profiles against Galactic objects provide information about the intervening ISM. These can be used to estimate distances to the objects using models for the distribution and velocity of the Galactic ISM. HI distance estimates for three morphologically distinct components in the above field were obtained from GMRT 1420 MHz HI absorption observations against these components.

The usefulness of observations such as the ones presented in this dissertation and future directions of research in this area are also discussed. This dissertation is expected to be the first step in a longer term campaign for a Galactic plane survey at a number of GMRT frequency bands. Such a survey will be very useful in the identification of new SNRs. Current SNR catalogues are known to be incomplete for small sized SNRs. Such a survey will separate thermal and non-thermal radiation effectively and allow the identi-

fication of compact, SNRs in the Galaxy.

The GMRT has only recently come to a stage where enough antennas are available in the interferometric mode to attempt the imaging of extended sources. A substantial fraction of the work done for this dissertation involved the debugging and calibration of the telescope, to enable the observations discussed above to be carried out. Further, large amounts of software were required to be written, both to carry out debugging activity as well as to enable flagging and calibration of telescope data in a semi-automated fashion. This aspect of the thesis work is discussed below.

Monitoring the data quality, the health of the system using the complex visibility function measured by an interferometer like the GMRT, identifying sources of data corruption, general debugging of the instrument, etc. all require sophisticated and efficient software for data analysis, browsing, and display. Extensive software was developed for this purpose in the form of general purpose object oriented libraries as well as programs for on-line and off-line data processing and display.

This GMRT data analysis software system was developed with the longer term goal of providing a software environment which could be used by other users of the telescope, as well for developing new data analysis and calibration techniques. A general purpose user interface library was also developed to make the application programs user-friendly. Using these libraries, programs for data editing, semi-automatic data flagging, on-line monitoring of the data, computation for antenna-based complex gains, amplitude and phase calibration, etc. were also developed. All this software was extensively used during the course of this dissertation. These libraries and programs have also been used by other researchers in the group, both to develop new software as well as for data analysis purposes.

For the purpose of imaging, it is necessary to measure the precise location of the antennas on the ground to an accuracy of a fraction of the wavelength. Further, one must also measure the time delay suffered by the signals from various antennas. The software discussed in the preceding paragraph was extensively used for the calibration of various instrumental parameters, including antenna positions and time delays. These measurements were used in a program for off-line phasing in the initial stages of this work and are now used for the on-line phasing of the telescope.

The complex visibility function, V, depends on a number of telescope parameters like the system temperature, sensitivity, antenna fixed delays, antenna positions, etc. During debugging, it was frequently required to view this data in various representations (e.g., Cartesian versus polar representation of complex numbers). Since the complex visibilities are a function of a multitude of parameters, and different debugging purposes require viewing V with respect to various quantities, it was necessary to develop a compact macro language parser to extract and display the data in a flexible and programmable manner.

Inteferometry at low frequencies poses new challenges in data calibration and analysis, which are interesting in their own right. Mapping here requires the use of different (and computationally intensive algorithms), compared to those used for mapping at higher frequencies. These algorithms are discussed in detail in this dissertation. Further, the volume of data for a typical GMRT observation is exceedingly large with varied sources of data corruption. Manual identification and flagging of bad data is therefore tedious, time consuming and fraught with human errors. During the course of this dissertation, procedures were evolved for the editing, calibration and mapping of low frequency data. New algorithms were developed to identify and flag bad data in a semi-automatic fashion. These algorithms were extensively used for the data analysis, substantially reducing the time required for data editing, as well as improving the quality of the edited data used for mapping purposes. These procedures and algorithms for the analysis of GMRT data, for the purpose of continuum imaging studies, are also discussed in this dissertation.

Algorithms for phase calibration, available in standard data reduction packages, are very sensitive to the presence of severely corrupted data. The problem of computation of antenna-based complex gains was formulated using complex calculus and the algorithm implemented as a general purpose program. This allowed insights into the working of this algorithm, and enabled devising of the variants which are robust in the presence of bad data. This was done by (1) automatically eliminating out-lying points, (2) doing two passes to eliminate dead/bad antennas. This algorithm was also used to identify and flag corrupted data in a semi-automatic fashion. It was extensively used for measuring antenna pointing offsets, on-line monitoring of the instrumental phase, closure errors in the telescope, as well as for antenna position and time delay calibration.

Techniques used to minimize polarization leakage in the system have not yet been realized for the GMRT. This leakage is a significant source of noise at 150 MHz and also contributes noise at all other bands, albeit at a lower level. An algorithm was developed to measure the leakage using *only* the co-polar visibilities currently produced by the GMRT correlator. This work also enabled us to understand the various sources of non-antenna based errors; this technique can now be used for better calibration of GMRT data.

New and robust algorithms for automatic data editing and better calibration are necessary for the analysis of data from any large scale observational project at low frequencies (such as the suggested multi-frequency Galactic plane survey). New software for on-line data monitoring and display as well as for generating flagging information during observations is also required to improve the data quality. Further, algorithms and associated software are also crucially necessary to detect RFI and possibly eliminate RFI affected data. Possibilities of future research in these directions is also discussed in this dissertation.