A Study of The Emission and Propagation of Radio Signals from Pulsars

by

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Dedicated to my parents...

CERTIFICATE

This is to certify that the thesis entitled **A Study of the Emission and Propagation of Radio Signals from Pulsars** submitted by Dipanjan Mitra, for the award of the degree of DOCTOR OF PHILOSOPHY of Jawaharlal Nehru University is his original work. This has not been published or submitted to any other universitv for any other degree or diploma.

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DECLARATION

I hereby declare that this thesis is composed independently by me at the Raman Research Institute, Bangalore, under the supervision of Prof. Dipankar Bhattacharya. The subject matter presented in this thesis has not previously formed the basis of the award of any degree, diploma, associateship, fellowship or any other similar title.

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A SYNOPSIS OF THE THESIS ENTITLED

"A STUDY OF THE EMISSION AND PROPAGATION OF RADIO SIGNALS FROM PULSARS"

More than thirty years since the discovery of pulsars, their radio emission mechanism is still very poorly understood. The major difficulty remains the lack of fully self consistent theoretical model of the pulsar magnetosphere. Empirical studies of the observed properties of pulsars, in particular their pulse shape and polarization, have however yielded important constraints for the theories to work within. This thesis is devoted mainly to an attempt to further these empirical studies, with an aim to learn a few additional things about the shape of the emitted pulse cone, the structure of the magnetic field as well as the distribution of interstellar electron density fluctuations.

Chapter 1

Chapter 1 gives a general introduction to pulsars and neutron stars relevant to the present work. In the beginning of the chapter we introduce the various pulsar parameters followed by a discussion on the basic pulsar properties namely radio pulse shapes and the polarization behaviour. This is followed by a discussion on the phenomenological models of pulsar emission and we briefly discuss one of the theoretical emission models. A brief outline of the internal structure of a neutron star and of the origin of the magnetic field is presented. Finally, the effects of propagation through the interstellar medium namely, dispersion and scattering, on the pulsed radio signal from pulsars are introduced.

Chapter 2

In chapter 2 we revisit the problem on the shape of pulsar radio emission beam. Characterizing the shape and frequency evolution of pulsar radio emission beams is important for understanding the observed emission. The various attempts by earlier workers investigating beam shapes have resulted in widely different conclusions. Using a carefully selected subset of the recently published multifrequency polarimetry observations of 300 radio pulsars (Gould & Lyne, 1998), we attempt to model the shape of pulsar beams. Assuming that the beam shape is elliptical, in general, and that it may depend on the angle between the rotation and the magnetic axes, we seek a consistent model where we also solve for the dependence of the beam size on frequency. The method employed is qualitatively different from earlier studies as we solve for the frequency evolution of the beam size rather than the evolution of the observed pulse widths. From the six-frequency data on conal triple and multiple component profiles, we show that

a) the pulsar emission beams follow a nested cone structure with at least three distinct cones, although only one or more of the cones may be active in a given pulsar;

b) each emission cone is illuminated in the form of an annular ring of width typically about 20% of the cone radius.

Although some slight preference is evident for a model where the beam is circular for an aligned rotator & latitudinally compressed for an orthogonal rotator, the possibility that the beam shape is circular at all inclinations is found to be equally consistent with the tlata. While the overall size scales as $P^{-0.5}$ (where **P** is the pulsar period) as expected from the notion of dipolar open field lines, we see no evidence in support of the evolution of beam shape with pulsar period.

Chapter 3

In chapter **3** we study, theoretically the expected evolution of the multipolar structure of the magnetic field of isolated neutron stars assuming the currents to be confined to the crust. Strong multipolar components of the magnetic field are often thought to play an important role in the radio emission from pulsars. Though the overall pulse emission window is decided by the dipole open magnetic field lines (as we argue in chapter 2), the 'illumination pattern' of the emitting region can be caused by the local multipolar structure of the magnetic field present at the surface of the neutron star. The multipolar components hence will decide the distribution of charges across the field lines, giving rise to the substructures in the integrated pulse profiles. Thus if the multipolar components evolve significantly with respect to the dipole, one would expect to see a corresponding chang, in the structure of the pulse. In our analysis we find that except for multipoles of very high order ($l \gtrsim 25$) the evolution is similar to that of a dipole. Therefore no signifirant evolution is expected in pulse shape of isolated radio pulsars due to the evolution of the multipole structure of the magnetic field. This fact seems to agree with observations where studies identifying multiple components in pulse profiles show that the number of components does not vary with the characteristic age of the pulsar.

Chapter 4

In chapter 4 we look for possible signatures of multipolar magnetic field in the polarization position angle traverse in pulsars. The position angle of the linear polarization is observed to sweep across the pulse window in a characteristic smooth S-shape which is interpreted as emission arising from regions where the underlying field is dipolar. The other effect observed in pulsars is that the pulse widths shows a systematic decrease with increasing frequency. This effect, known as radius-to-freqnency mapping, in interpreted as emission at higher frequency being emitted from lower altitudes from the stellar surface while emission at lower frequencies being emitted at higher altitudes.

In chapter **3** we have considered the possibility that multipolar component of the magnetic field in the surface of neutron stars, can be invoked to explain the complexity in the observed pulse profiles. However the radio emission region, which is thought to be located far away from the surface, may be much closer to dipole due to the steep fall off of multipole fields away from the star. Nonetheless, due to radius-to-frequency mapping, at higher frequencies one expects to probe regions closer to the stellar surface where the magnetic field could be non-dipolar. As a result, the smooth S-shaped curve of the polarization position angle sweep is expected to develop a kinkiness at higher frequencies. We have simulated the magnetic field structure around the neutron star with a dipole and quadrupole component of the magnetic field, and produced the polarization position angle as a function of stellar altitudes. The kinkiness in the curves are evident.

Further we have checked this effect on the multifrequency polarimetric data of PSR B0329+54 spanning a frequencv range from 408 MHz to 4.8 GHz. The full polarization single pulse data on this pulsar was obtained from the European Pulsar Network archive at frequencies 1.4 GHz, 2.7 GHz and 4.8 GHz. A single pulse analysis of this pulsar was done to get, the multifrequency polarization position angle curves. We find that tlie polarization position angle has developed a kinkiness at and above 2.7 GHz. We interpret the effect to be due to the presence of quadrupolar magnetic field component along with the dipole. We show that the simulated curve for the polarization position angle is in good agreement with observation. However, due to large number of unknowns in the problem (cf. tlie orientation and strength of the quadrupole with respect to the dipole) it is not possible to uniquely determine the true magnetic field structure from this analysis.

Chapter 5

In chapter 5 we report measurements of scatter broadening of pulsars at 327 MHz using the Ooty Radio Telescope. The radio pulse signal, originating from the pulsar, travels a long way before it reaches an earth-bound observer through the interstellar medium. The density fluctuations of the ionized component of the interstellar medium causes the pulsar signal to be scattered. As a result the pulse shape gets broadened in time and it develops an exponential tail. Measurement of the scatter broadening (τ_{sc}) is thus an useful quantity to understand the density fluctuations in the interstellar medium. However τ_{sc} values exists only for —145 pulsars out of tlie ~1000 pulsars known today. Hence a systematic survey for measuring the scatter broadening in a large number of pulsar directions where such data are not available yet,, was undertaken. We did our observations in two phases. For the first phase me selected 27 high dispersion measure pulsars. New measurements of τ_{sc} for the 27 pulsars at 327 MHz are presented in this chapter. These measurements significantly improve on the available set of measurements for pulsars with dispersion measures in the range 100 to 250 pc cm^{-3}. These measurements also sample an important section of the galactic volume which should render better modeling of the electron density distribution. The dependence of the scatter broadening on the tlispersion measure is discussed arid modeled based on the new data combined with earlier similar measurements.

In the second phase we selected pulsars in tlie direction of the Gum Nebula. In a study to obtain pulsar distances and the electron density model of the galaxy, Taylor & Cordes (1993) used the shapes and locations of various HII regions derived from existing optical arid radio observation. In their model the Gum Nebula (because of its proximity) has been given special attention apart from the already existing HII regions which closely follow the spiral arms of the galaxy. However, as also suggested by Taylor and Cordes, inadequate knowledge about the variations of the electron density and its fluctuations across the region makes it difficult to allow construction of a meaningful model for the parameters of the Gum Nebula. We report τ_{sc} measurements for 21 pulsars observed in that direction which would improve our understanding of this region.

Parts of this thesis have been published in the following papers:

- " Evolution of Multipolar Magnetic Fields in Isolated Neutron stars", Mitra D., Konar S. & Bhattacharya D., 1999, MNRAS, 307, 459
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- "Shape of Pulsar Beams Revisited", Mitra D. & Deshpande A. A., 1999, Bull. Astr. Soc. India, 27, 203, conference procceding for XVIII Annual Meeting of Astronomical Society of India.
- "Measurement of scatter broadening for 27 pulsars at 327 MHz", R. Ramachandran, D. Mitra, A. A. Deshpande, D. M. McConnell and J. G. Ables, 1997, MNRAS, 290, 260

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