The Evolution of the Magnetic Fields of Neutron Stars : The Role of the Superfluid States in their Interiors

A Thesis
Submitted for the Degree of
Doctor of Philosophy
in the Faculty of Science

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DECLARATION

I hereby declare that the work presented in this thesis is entirely original, and has been carried out by me at the Raman Research Institute, Bangalore, under the auspices of the Department of physics, Indian Institute of Science, Bangalore. I further declare that this has not formed the basis for the award of any degree, diploma, membership, associateship, or similar titles of any university or institution.

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SYNOPSIS

This thesis is devoted to an investigation of the secular decay in the magnetic fields of neutron stars. The magnetic field of a neutron star plays a central role in its evolution – like the mass of a gaseous star does in stellar evolution. Very soon after pulsars were discovered it was suggested by Ostriker and Gunn that their magnetic fields may be decaying in very short timescales of the order of a few million years. It was however pointed out by Baym, Pethick and Pines (1969) that there is a fundamental difficulty in understanding the decay of the magnetic fields of neutron stars. In the classical picture this difficulty arises due to the astronomically long ohmic dissipation timescales ($\sim 10^{15}$ yr) that are implied by the enormously high electrical conductivity. In the quantum picture, according to which the protons in the interior will be in a superconducting state, it is even more difficult to understand the decay of magnetic fields.

Regardless of the conceptual difficulties, the observational evidence gathered during the past 25 years does seem to indicate that magnetic fields of neutron stars may indeed be decaying. **A** further twist to this dilemma is provided by the observational fact that the overwhelming majority of neutron stars with low magnetic fields are in binary systems. Therefore there have been attempts in the literature to seek a causal connection between the mechanism of field decay and the history of a neutron star in a binary system.

According to one hypothesis (Taam and van den Heuvel 1986; Romani 1990), the decay of the magnetic field may be related to the accretion of matter itself. We shall not pursue this mechanism in this thesis. Instead we will investigate in detail an alternative suggestion that has been made recently.

Soon after the discovery of the microscopic theory of superconductivity by Bardeen, Cooper and Schriefer – and many years before the discovery of neutron stars – A.B. Migdal and V.L. Ginzburg predicted that the neutron fluid in the interior of a neutron star would be in a superfluid state, and the protons in a superconducting state. It has since been widely accepted that the existence of superfluid states can and will have many important astrophysical consequences. Superfluidity of the neutrons was first invoked to explain the phenomenon of "glitch" in radio pulsars. More recently the superconductivity of the proton fluid was given a central role in trying to explain the decay of magnetic fields in neutron stars.

According to this novel suggestion (Srinivasan 1989, Srinivasan *et al.* 1990), the magnetic flux trapped in the superconducting interior is expelled from it as a consequence of the slowing down of the neutron star. This model invokes interpinning between the vortices in the neutron superfluid (parallel to the rotation axis of the star) and the quantized fluxoids in the proton superconductor (parallel to the magnetic axis). *This thesis is devoted to a detailed investigation of this novel suggestion.* The material in this thesis is organized as follows.

Chapter 1: In the first chapter a detailed introduction is given to the structure of the interior of a neutron star. Then the rotational history of neutron stars in binary systems is reviewed and the necessary formulae for the ensuing detailed calculations are summarized.

Chapter 2: This chapter begins with a brief review of the current ideas on the origin and evolution of magnetic fields of neutron stars. Then the scenario of spindown induced flux expulsion from the superconducting interior (SIF model) is described in some detail. The rest of the chapter is devoted to a detailed analysis of the magnetic field evolution of solitary neutron stars, as well as those born and processed in binary systems within the premise of the SIF model. In the latter category, a separate account is given of neutron stars with massive, intermediate mass and low mass stellar companions. A comparison is made between the predictions of the model as borne out by detailed calculations and the observed magnetic fields of neutron stars.

Chapter 3: In the simple model of flux expulsion explored in chapter 2 it was assumed that the fluxoids pinned to the neutron vortices could be drawn out at arbitrary speeds decided only by the spindown rate of the neutron star. Such a simplified picture ignores several other important forces that may be acting on the magnetic flux tubes as they move through the degenerate electron gas. For example, it is well known from laboratory experience in type II superconductors that a moving fluxoid will experience a "drag" force due to scattering of electrons off the flux tubes. Such a drag force can restrict the motion of the flux tubes. In addition, the quantized flux tubes may experience a buoyancy force, as well as forces that arise due to curvature of these flux tubes as they are dragged out of the superconducting interior. In this chapter all these forces are carefully taken into account and the results of chapter 2 are re-examined for solitary, as well as neutron stars in binary systems.

Chapter 4: The underlying theme of chapters 2 and 3 was that if the vortices and fluxoids were interpinned, then, as the vortices move out in response to the slowing down of the star they will drag the flux tubes with them. If this is indeed the case then it is reasonable to ask whether there could be a back reaction on the rotation of the star itself. For example, it is customarily assumed that the neutron superfluid in the core will more or less instantaneously re-adjust its rotation rate to match with that of the crust. This need not be true if the vortices are tangled up with the fluxoids and are therefore not able to quickly re-adjust their positions in response to a sudden spinning up or spinning down of the crust. This question has not been considered in the literature so far, and is addressed for the first time in this chapter. Several interesting consequences of the interplay between the magnetic evolution of the neutron star and its spin evolution are described.

Chapter 5: In this final chapter we gather together all the new results and conclusions described in this thesis.