Superfluid effects on thermal evolution and rotational dynamics of neutron stars
by Michelle Beauvais Larson

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics
Montana State University

Abstract:
This thesis examines the observational consequences of superfluidity on thermal evolution and rotational dynamics of neutron stars. Temperature measurements of older neutron stars (tage >~ 10^6 yrs) indicate that these objects are heated. A promising candidate heat source is friction due to differential rotation between the neutron star crust and the superfluid it is thought to contain. We study the effects of superfluid friction on the long-term thermal and rotational evolution of a neutron star and obtain constraints on the strength of the frictional coupling between the stellar crust and the interior superfluid. The second part of this thesis provides simulations of glitches (sudden jumps in spin rate) in isolated pulsars. With the aim of distinguishing among different theoretical explanations for the glitch phenomenon, we study the response of a neutron star to two types of perturbations to the vortex array that threads the superfluid interior. Both mechanisms produce acceptable fits to glitch observations in the four pulsars we study. The two models make different predictions for the generation of internal heat and subsequent enhancement of surface emission. Future glitch observations coordinated with surface emission measurements will play a key role in distinguishing between the two glitch models we investigate.

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Michelle Beauvais Larson

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APPROVAL

of a dissertation submitted by

Michelle Beauvais Larson

This dissertation has been read by each member of the dissertation committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date 04/02/01

The Road Not Taken

Two roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveler, long I stood
And looked down one as far as I could
To where it bent in the undergrowth;

Then took the other, as just as fair,
And having perhaps the better claim,
Because it was grassy and wanted wear;
Though as for that the passing there
Had worn them really about the same,

And both that morning equally lay
In leaves no step had troden black.
Oh, I kept the first for another day!
Yet knowing how way leads on to way,
I doubted if I should ever come back.

I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I-
I took the one less traveled by,
And that has made all the difference.

- Robert Frost

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ABSTRACT

This thesis examines the observational consequences of superfluidity on thermal evolution and rotational dynamics of neutron stars. Temperature measurements of older neutron stars ($t_{\rm age} \gtrsim 10^6$ yrs) indicate that these objects are heated. A promising candidate heat source is friction due to differential rotation between the neutron star crust and the superfluid it is thought to contain. We study the effects of superfluid friction on the long-term thermal and rotational evolution of a neutron star and obtain constraints on the strength of the frictional coupling between the stellar crust and the interior superfluid. The second part of this thesis provides simulations of glitches (sudden jumps in spin rate) in isolated pulsars. With the aim of distinguishing among different theoretical explanations for the glitch phenomenon, we study the response of a neutron star to two types of perturbations to the vortex array that threads the superfluid interior. Both mechanisms produce acceptable fits to glitch observations in the four pulsars we study. The two models make different predictions for the generation of internal heat and subsequent enhancement of surface emission. Future glitch observations coordinated with surface emission measurements will play a key role in distinguishing between the two glitch models we investigate.

CHAPTER 1

INTRODUCTION

Neutron Stars: Creation and Discovery

Neutron stars are a product of the continuously evolving Universe. Gas clouds gather to form new stars which shine by fusing fundamental elements, beginning with hydrogen and continuing up to iron for the highest mass stars. The end of a star's life brings a recycling of the gas that created it, now rich with heavier elements, along with a compact remnant which is left behind to join the stellar graveyard.

Neutron stars, together with white dwarfs and black holes, make up the population of stellar remnants in the Universe. Although the mass distribution of the progenitor population is not yet known in detail, in general low mass stars ($M \lesssim 8 M_{\odot}$, where $M_{\odot}$ is the mass of our Sun) evolve into white dwarfs, higher mass stars ($8 M_{\odot} \lesssim M \lesssim 25 M_{\odot}$) evolve into neutron stars, and the highest mass stars ($M \gtrsim 25 M_{\odot}$) create black holes (Ergma & van den Heuvel 1998). The closest known neutron star is 200 light years from Earth[1] (Walter 2000); beyond it our Galaxy alone contains at least 10 million neutron stars according to current estimates. A neutron star is a compact, extraordinarily dense star having a mass $M \simeq 1.4 M_{\odot}$, a radius $R \simeq 10$ km, and a strong magnetic field $10^{12} \lesssim B \lesssim 10^{14}$ G (inferred from dipole spin-down of the star)[2]. A neutron star is supported by the pressure of degenerate fermions (neutrons

[1]This neutron star is designated RX J185635-3754

[2]Compare this to the Earth's magnetic field of $B_{\oplus} \simeq 0.5$ G.

and electrons). The average density of a neutron star is approximately twice that of nuclear density (where nuclear density is $\rho_o \simeq 2.8 \times 10^{14}$ g cm^{-3}). Most of the nuclei in the stellar interior are dissociated into their constituent particles (neutrons, protons and electrons). At such high densities, the equilibrium state of the matter is about 90% neutrons by mass. The density of a neutron star is similar to that of a nucleus, but overall, the star is a macroscopic environment of ultra-dense matter, unlike anything studied on Earth.

Neutron stars found their place in theoretical astrophysics long before they were observed. Baade and Zwicky (1934) introduced the term *neutron star* when they suggested that a supernova results from the evolution of a main-sequence star into a remnant composed primarily of neutrons[3]. Oppenheimer and Volkoff (1939) derived the general relativistic equations which describe the internal structure of a neutron star. Migdal (1959) originally suggested that the interior of such stars would be superfluid. Despite obvious interest in these remarkable objects, neutron star research remained firmly in the theoretical arena, since it was believed that neutron stars would be difficult, if not impossible, to detect. This situation changed, however, in 1967 with the first discovery of a radio pulsar[4] by graduate student Jocelyn Bell and her advisor Anthony Hewish at the Jodrell Bank Observatory in Manchester, England (Hewish et al. 1968). This discovery earned Hewish and fellow radio astronomer Martin Ryle the Nobel Prize in Physics in 1974. In the months surrounding Bell's observation of periodic radio pulses, Pacini (1967) and Gold (1968) suggested that

[3]The neutron itself had only been recently discovered by Chadwick in 1932.
[4]This radio pulsar now bears the designation PSR 1919+21.

the pulsations could be produced by a rapidly rotating, magnetized neutron star. Further observations have confirmed this basic picture. The term *pulsar* is now used to describe a rotating neutron star which has a pulsed electromagnetic radiation signature.

Neutron stars have many manifestations. In rotation-powered pulsars, the type discovered by Jocelyn Bell, the star's magnetic field converts rotational energy into electromagnetic radiation. This process slows the star's rotation rate over time. The radiation signal appears pulsed as the star's rotation sweeps the radiation beam across our line of sight. Neutron stars in binary systems can accrete matter from a companion; the matter surrounds the neutron star in a gaseous disk. These accretion-powered pulsars convert the gravitational potential energy of the accreted matter into photons. These systems can produce low-luminosity x-ray emission as well as strong x-ray bursts. The discovery of the first *magnetar* occurred in 1998 (Kouveliotou et al. 1998). Magnetars are rotating neutron stars which have extremely high magnetic fields ($B \simeq 10^{14}$ G), and exhibit a variety of energetic phenomena that are probably driven by decay of their intense magnetic fields. Anomalous x-ray pulsars (AXP's) are slowly rotating neutron stars which exhibit strong x-ray emission. Soft gamma repeaters (SGR's) are observed to emit multiple, intense bursts of low-energy gamma-rays, and are thought to be rotating neutron stars as well. AXP's and SGR's are probably two observational manifestations of magnetars. The work in this thesis will focus on isolated, rotation-powered pulsars, which we discuss in more detail next.

Neutron Stars: Structure

Because of their small size and great distance from Earth, astronomers have yet to resolve an isolated neutron star into an observable disk which can be imaged and studied. Physical parameters such as the mass and radius must be determined indirectly. In 1974, Rhodes and Ruffini placed theoretical limits $0.2M_\odot \lesssim M \lesssim 3.5M_\odot$ on the mass required to gravitationally bind a neutron star. Considerable progress has been made in the determination of the mass by observing neutron stars in binary systems. Measurements and upper limits of the masses of 14 binary systems which contain at least one neutron star are presented in Figure 1. In these cases, study of the orbital dynamics has provided mass determinations which span a remarkably narrow range, with a mass of $M \simeq 1.4M_\odot$ being in agreement with all the data (Thorsett & Chakrabarty 1999). Observational values for neutron star radii have been obtained by fitting thermal emission measurements with blackbody radiation spectra and atmospheric models. These measurements yield neutron star radii of 8 - 15 km. Theoretically, neutron star radii can be calculated after assuming a mass for the star and an equation of state of the interior. The exact equation of state for neutron star matter is unknown, mostly due to uncertainties in nucleon-nucleon interactions above nuclear density. Equations of state differ above nuclear density. Soft equations of state (e.g., Baym, Pethick & Sutherland 1971), for which the matter is relatively compressible, predict a radius of $R \simeq 8$ km for a $1.4M_\odot$ star. Stiff equations of state (e.g., Pandharipande & Smith 1975), for which the matter has relatively low compressibility, predict $R \simeq 15$ km, for the same mass. The work in

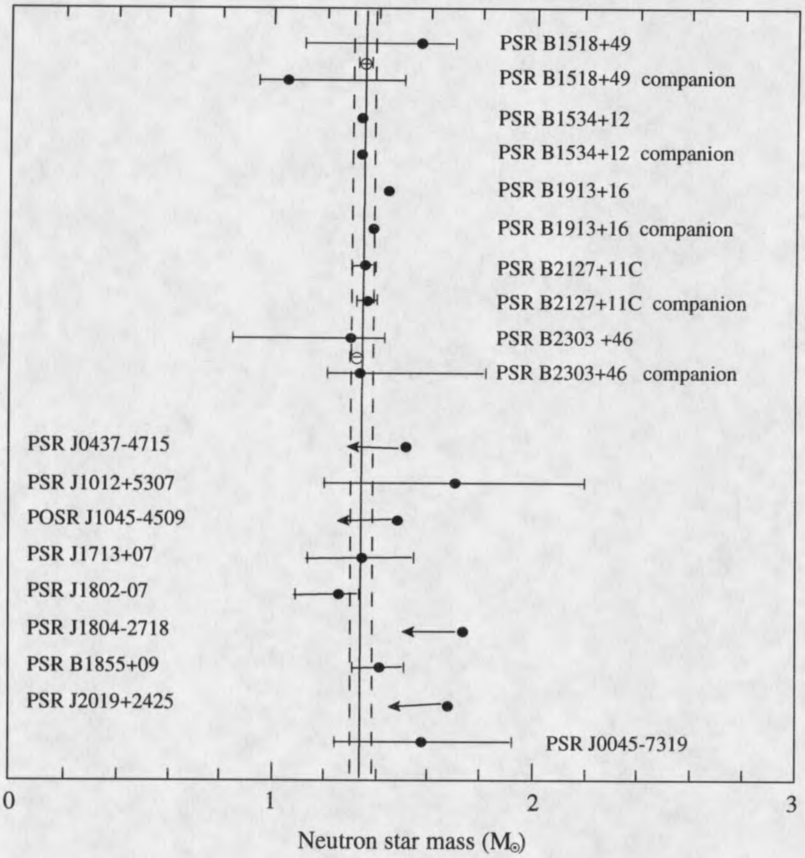

Figure 1. Neutron star masses from observations of radio pulsar systems. Five double neutron star systems are shown at the top of the diagram. In two cases, the average neutron star mass in a system is known with much better accuracy than the individual masses; these average masses are indicated with open circles. Eight neutron star white dwarf binaries are shown in the center of the diagram, and one neutron star-main-sequence star binary is shown at bottom. Vertical lines are drawn at $M = 1.35 \pm 0.04 M_{\odot}$, the range which is consistent with all measurements (from Thorsett & Chakrabarty 1999).

this thesis uses the medium equation of state of Friedman & Pandharipande (1981). Future determinations of the mass-radius relationship in neutron stars promise to constrain the equation of state of nuclear matter in a way not currently possible in terrestrial laboratories.

Equation of state calculations also provide models for the physical state of neutron

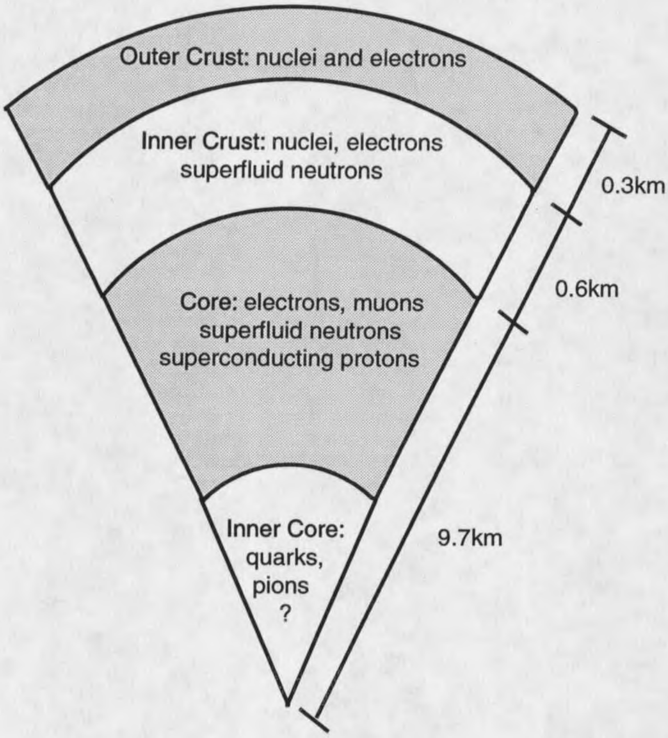

Figure 2. The internal structure of a $1.4M_{\odot}$ neutron star. Dimensions are representative of a star with a moderate equation of state.

star matter as a function of density. The current view of the neutron star interior consists of several distinct layers (Fig. 2). These layers include the atmosphere, the outer and inner crust, and the core. Below the thin atmosphere (of thickness less than 1 cm; Miller 1992), lies a solid outer crust. The outer crust consists of a lattice of neutron-rich nuclei, immersed in a relativistic, degenerate electron gas. Above a density of $\sim 4.3 \times 10^{11}$ g cm^{-3}, the *neutron drip* density, nuclei coexist with a neutron liquid and degenerate electrons. The inner crust extends from neutron drip to near nuclear density. The nuclei become more neutron-rich with increasing density, having mass numbers of several hundred near nuclear density. Neutrons in the inner crust are believed to be in superfluid form. Superfluidity is a phenomenon that occurs when bosons condense into their ground state. Systems of fermions can condense into a superfluid if they can form Cooper pairs. In neutron star matter, pairing occurs through the strong force to form n-n and p-p paired states. Neutrons in the inner crust can pair in a singlet $^1S_0$ state. In the core, both neutrons and protons can form a superfluid, with the proton superfluid being superconducting due to the proton charge. Neutrons in the core pair in a triplet $^3P_2$ state, while the protons are in a $^1S_0$ state. Cooper pairing occurs when the temperature falls below a critical temperature. Calculations of critical temperatures for these pairing states, as functions of density, give $T_{\rm crit} \simeq 10^9 - 10^{10}$ K (e.g., Ainsworth, Pines & Wambach 1989; Wambach, Ainsworth & Pines 1991). The core consists mostly of superfluid neutrons with a few percent superconducting protons, normal electrons and muons. The inner core may contain exotic matter such as quarks, pions or kaons.

A pure superfluid has macroscopic occupation of the ground state. Such a system flows without friction, and cannot rotate as a whole. However, when the superfluid is in a container which is rotating above a critical rotation rate, it is thermodynamically favorable for the superfluid to rotate as well. Superfluid rotation is achieved by the formation of an array of vortex lines within which the fluid is normal. This phenomenon is observed in rotating He II in terrestrial laboratories (see, e.g.Yarmchuk & Packard 1982). At the rotation rate of a typical neutron star, the superfluid is also rotating and contains $\sim 10^{17}$ vortices, which will be discussed in Chapter 3. Friction associated with the normal fluid in the vortex cores generates heat and exerts torque

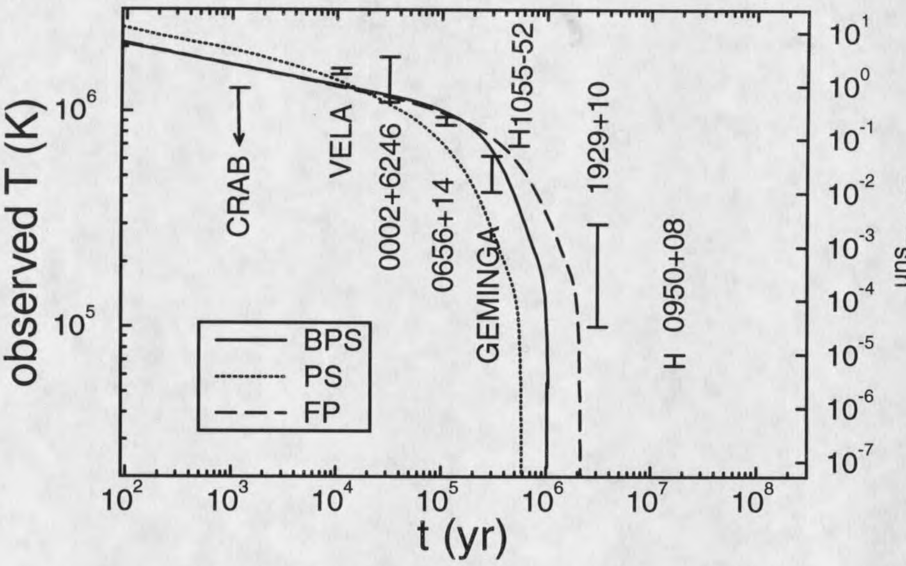

Figure 3. Neutron star thermal evolution, observations and cooling curves. Standard cooling curves are shown for stars with $M = 1.4M_{\odot}$ for three different equations of state: PS (Pandharipande & Smith 1975), FP (Friedman & Pandharipande 1981) and BPS (Baym, Pethick & Sutherland 1971). Cooling simulations are from Van Riper (1991). Observational measurements (and one upper limit) are also indicated. See Tables 2 and 3 of Chapter 2 for references to the observational data.

on the crust. The thermal evolution and rotational dynamics of a neutron star are affected by the rotation of the superfluid interior. The observable consequences of superfluidity in neutron stars are the focus of this thesis.

Neutron Stars: Cooling

Unlike main sequence stars, neutron stars are no longer undergoing nuclear fusion. A neutron star can be thought of as a hot ember, which looses heat to its surrounding over time. Since the 1980's, space-based x-ray telescopes have made observations of the thermal emission from neutron star surfaces possible. By observing neutron stars of different ages, a picture of how a neutron star cools with time has been assembled (see Tsuruta 1998 for a comprehensive review). Figure 3 shows observational measurements and upper limits for eight neutron stars, with several theoretical cooling predictions for different equations of state.

When a neutron star is formed during a supernova explosion, its internal temperature is approximately 10^{11} K. Neutrino emission processes quickly cool the star to below $T \simeq 10^{10}$ K, on a timescale of about a day. A neutron star becomes isothermal within $\sim 10^4$ yrs after its birth (Van Riper 1991; Umeda et al.1993). Neutrino emission dominates the cooling until the internal temperature falls below $T \simeq 10^8$ K, corresponding to a surface temperature of $T_{\rm obs} \simeq 10^6$ K, at an age of approximately $t_{\rm age} \simeq 10^5$ years. At this stage photon cooling from the surface becomes more important than neutrino losses.

How quickly a neutron star cools depends on the equation of state, relevant cooling processes, and possible internal heat sources. Constraints can be placed on physical processes within the star by making comparisons between thermal observations and theoretical cooling models. For standard cooling models the dominant neutrino cooling process in the core is the modified URCA[5] process. The reaction is:

$$n + n \rightarrow n + p + e^- + \bar{\nu}_e$$

$$n + p + e^- \rightarrow n + n + \nu_e. \tag{1.1}$$

If the proton fraction in the core is high ($\gtrsim$14%), neutrino cooling occurs via the much faster direct URCA process (see, e.g.Prakash 1994). In the crust, the dominant neutrino cooling process occurs by electron-ion bremsstrahlung, the scattering of relativistic electrons with nuclei. Energy loss through photon cooling at the surface of the star occurs essentially as blackbody radiation (modified by the atmospheric composition). Cooling rates are presented in detail in Chapter 3.

Comparison of cooling models with thermal observations indicate that older neutron stars are heated (see Fig. 3). PSR 1929+10 and PSR 0950+08, have significantly higher temperatures than the cooling calculations can explain. Chapter 2 will investigate a promising internal heat source that can explain this puzzle.

Neutron Stars: Spin Behavior

Typical radio pulsar rotation periods lie between several milliseconds and several seconds. Isolated radio pulsars are observed to spin down at remarkably steady rates. The accuracy and predictability of the spin period increase has distinguished radio pulsars as 'the most accurate clocks in the Universe'.

Many pulsars have been observed to experience sudden spin-ups, or *glitches*, on top of their steady spin-down. Glitches produce fractional changes in rotation rate

[5]The URCA reaction, which is a sink for the star's energy, gets its name from the URCA casino in Rio de Janeiro, which is a sink for money.