NASSP MSc STUDENT PROJECTS

PULSAR RESEARCH UNIT

UNIVERSITY OF THE WITWATERSRAND
JOHANNESBURG PLANETARIUM
HARTEBEESTHOEK RADIO ASTRONOMY OBSERVATORY

Pulsars

Pulsars are key objects in astrophysics. In them, matter exists under conditions so extreme that we cannot even begin to imagine how they might be realised in any laboratory. They are superdense remnants of stellar collapse which contain a mass of approximately 1.5 suns compressed into a ball approximately 15 km in diameter, and which spin at rates that range from once per second to as much as 750 times per second. Their surface is solid crystalline iron, and would ring like a bell were it to be hit with an hammer.

Descending into their interior, within tens of metres from the surface, the iron nuclei begin progressively to ooze neutrons until eventually, at a depth of several hundred metres, the nuclei dissolve completely. The free electrons combine with free protons to form neutrons. The bulk of the pulsar thus consists of neutrons. The density of matter in the pulsar has now risen from that of crystalline iron by 10 orders of magnitude to 10^{17} kg / m^3. The pressures are also fantastically high, and the neutrons are forced closer together than is possible in a nucleus. At this range, they form weak dynamical S-state bonds. The neutronic material thus becomes a boson fluid. Its temperature is below critical, so the entire interior of the pulsar becomes superfluid and flows without friction. Deeper in the star, as the pressures rise further, P-state bonds are formed, making the inner mantle a superfluid of a different type to that in the outer mantle. We don't know what happens at the core, but the conditions are thought to be right for quark deconfinement. If so, the core is strange matter.

As you see, a pulsar is a very exotic object. But there is more. In stellar collapse, the total magnetic flux is conserved. So, in a pulsar, the magnetic field of a star larger than our sun is compressed into 15 km. This makes the magnetic field at the surface of a typical pulsar about 10^{10} gauss, which is fantastically huge - over 9 orders of magnitude larger than the most powerful laboratory field. The effect of this field is to produce a beaming by which pulsars were first detected. Since this field rotates with the pulsar, it induces an electric field at the surface which, at the polar caps, rips electrons out of the iron surface and hurls them into space along the magnetic field lines where they accelerate, cascade, and radiate. Furthermore, the rotation speeds near the pulsar surface are sufficiently close to the speed of light, and the mass of the pulsar so huge, as to make relativistic effects, general and special, important.

In short, pulsars are natural, cosmic laboratories, provided by nature herself, in which the properties of matter under extreme conditions may be observed. In fact, they are the only laboratories of this kind available. Black holes are denser, but apart from trace effects and radiation signatures, they cannot be seen. White dwarf stars are significantly less compact. The matter in them is not subject to conditions that are anywhere near as extreme. There is therefore no other astronomical object that provides the opportunities provided by pulsars for testing physical theories. And the range of theories that can be tested is large, ranging from elementary particle theory and the theory of strange matter, to nuclear physics, superfluidity, superconductivity, nuclear theory, solid state, and electrodynamics. And, interestingly, pulsars also provide a significant new testing ground for general relativity.

The Pulsar Research Unit

A sample of nearly 30 pulsars have been monitored at the Hartebeesthoek Radio Astronomy (HartRAO) since 1986. Claire Flanagan, who set up the pulsar monitoring programme, and her co-workers have accumulated some of the best long-term data sets on pulsars in the world. This data potentially holds the key to resolving some of the controversies surrounding pulsars and their properties. Many features of this data remain largely uninterpreted. Two years ago, Beate Woermann instigated the formation of a Pulsar Research Unit. This Unit brings together a wide range of expertise which includes observational and data analysis skills, technical and electronic know-how, and theoretical, computational and numerical knowledge and expertise. It currently consists of the following persons: Claire Flanagan, George Nicholson, Beate Woerman, Sarah Buchner, Adrian Tiplady, and Fabio Frescura. The unit is based at the University of the Witwatersrand, meets regularly at the Johannesburg Planetarium and at the School of Physics, and works closely with HartRAO, which runs the monitoring programme.

The HartRAO data is rich, and could be used in a wide range of programmes and projects. These range from the seriously theoretical to numerical and computational modelling and analysis. The expertise represented in the group is sufficiently broad to allow projects to be tailored to accommodate individual student preferences for each of these project types. Below we outline some projects that are currently in progress, and invite students to apply for participation in these. Should a student have a particular interest not represented in these projects but within the gambit of pulsar research, we invite that student to submit a project proposal to the Pulsar Research Unit for consideration. All of our projects are extendible to a PhD. Some of our projects involve aspects in which the current members of the Pulsar Research Unit have little or no expertise. Students willing to undertake research in those areas will thus have the opportunity to make a valuable contribution to the Unit and to establish themselves as the local experts in those areas. Students working with the Pulsar Research Unit would be registered for their Masters degree in the School of Physics at the University of the Witwatersrand.

CURRENT PROJECTS

1. Glitch models

Glitches are sudden dramatic increases in the rotation rate of a pulsar. These are thought to be due to disturbance of the outer layers of the superfluid mantle. The disturbance raises the neutronic material in these layers above the critical point, resulting in a loss of superfluidity. They thus become frictive and couple to the crust, delivering an huge amount of angular momentum to it and resulting in the observed spin-up. The entire process is known to take less than a few seconds. The star then recovers and, in months or years, returns to its former equilibrium or else settles into a new one. The HartRAO data contains a significant number of glitches and well resolved post-glitch recoveries.

Glitches are important. They are probes into the properties and behaviour of the neutron star interior. In fact, it is probable that they only such probes available. The object of this project is to investigate the influence of the pulsar interior on the observed recovery process. Aspects of this project include the development of theoretical models and/or the implementation of computer simulations of glitch and glitch recovery processes. The ultimate aim is explaining the observations made at HartRAO. The student will be required to undertake an extensive literature search; to collect, compile, collate, and to understand the work done in this field; and to present a comprehensive survey of the state of the art for use by the Research Group.

2. Precession

According to current theory, pulsars should not precess. It predicts that the superfluid interior should damp any excited precessional mode within several hundred cycles. Any precessional motion in a pulsar should therefore not persist for more than a few minutes. Yet the data sets for several pulsars display systematic oscillations in the pulse arrival times which have continued for decades. An explanation offered for these oscillations is precession. At this stage, this explanation is little more than conjecture, based on a comparison of observed and calculated periodicities. If a pulsar is actually precessing, the precessional motion should manifest itself in a variety of characteristic signatures on several observable effects.

The object of this project is to investigate systematically, by theoretical and/or computer models, the effect of precession on pulsar observations. Preliminary work on this problem has already been done, but the models developed thus far need substantial modification and extension. Work done so far includes elementary investigation of the precessional behaviour of dense non-magnetic axisymmetric objects. The non-axisymmetric case has not yet been usefully investigated. These models need extension to include the effects pulsar magnetic field. The aim of this project is to identify distinctive precessional signatures, to estimate the size of the expected effects, and to search for those effects in the HartRAO data sets, with the object of obtaining a definitive answer on the question of whether pulsars precess. The student will be required to undertake an extensive literature search on this subject; to collect, compile, collate, decipher and extend the work already done in this field; and to present a comprehensive survey of the state of the art for use by the Research Group.

3. Noise and Random Processes

Many natural phenomena are stochastic and manifest themselves in the data as noise and random variation. Each stochastic phenomenon has characteristic signatures and time scales. To understand the physical processes occurring, it is necessary to develop theoretical models that incorporate and characterise these random variations, methods for their analysis, and numerical and computer techniques that identify and disentangle them. In pulsars, these manifest themselves as variations in rotation rate, and in intensity fluctuations. They are thought to originate in crust quakes, core quakes, thermal pulses, pinning and unpinning of superfluid vortices, irregular drag of the magnetic field through the pulsar magnetosphere, randomness in the emission processes of particle and electromagnetic radiation, and random fluctuations in the coupling between the superfluid core and the crust.

Available projects include the investigation and characterisation of noise of different types using tools such as structure functions, autocorrelation functions, wavelet analysis, transform techniques, and testing the techniques developed on simulated data. The ultimate objective is understanding the HartRAO pulsar data by identifying the various pulsar processes responsible for the observed noise and modelling of these processes to predict their characteristic signatures and expected strengths.

4. General Relativistic Effects

Pulsars are sufficiently dense and rotate sufficiently rapidly to distort significantly the space-time in their immediate vicinity. It is already known that the general relativistic effect of frame dragging substantially alters the predictions of classical electrodynamics as regards the emission of particles from the pulsar polar caps and the properties of the radiation caused by their subsequent cascading in the pulsar magnetic field. It is probable also that general relativistic phenomena will have significant implications for possible precessional signatures and may provide further tests for general relativity.

This project involves the building of general relativistic models for the processes described under the other project headings described above, and their computer implementation, with a view to investigating whether the classically predicted results are significantly altered by general relativistic effects. This is a new project and is suitable for a student with a strong theoretical bent.

5. Effect of the Interstellar Medium on the Pulsar Signal

The interstellar medium is not a vacuum, but is a tenuous cold plasma which has a significant and measurable effect on the pulsar signal. In fact, the pulsar signal can be used to probe the electron density of the medium, and the effect of the medium can be used to estimate the distance to the pulsar. The effect of the interstellar medium becomes particularly interesting in cases where the pulsar signal is irregularly intercepted by nebulae, dust clouds and supernova remnants and can lead to interesting effects such as refractive and diffractive interstellar scattering. In some cases, this can lead to large variations in signal intensity due to the formation of diffraction patterns and caustic curves along the Earth's orbit.

The Pulsar Research Unit has very little expertise in the field of interstellar scattering and is keen to develop rapidly its knowledge and skills in this area. This project includes an extensive literature survey in which the student is expected to collect, collate and understand the work already done in this area, and to develop and investigate the associated phenomena either theoretically or by computer modelling. The HartRAO data displays intensity variations that are probably due to the action of the interstellar medium on the pulsar beam. In some cases, this effect is dramatic. The object of this project is to understand and explain the HartRAO data.

6. Other Projects

While the projects listed above represent to fair accuracy the current interests of the Pulsar Research Unit, many aspects of pulsar physics are not yet represented in them. For example, no project presently involves investigation of the behaviour and properties of the superfluid interior, the action of the superfluid vortices on the motion of the crust, the action and effect of crust and core quakes on the rotational motion of the star, the detailed shape and strength of the radiation beam, or detailed modelling of the pulsar magnetosphere. All of these are relevant to the research of the group and will eventually need to be investigated. Students wishing to commence work on any of these aspects are requested to submit a detailed proposal for consideration by the Unit.

Contact Details

Should you wish to discuss any project or aspects of these projects, please contact:

For Observational, Electronic, and Computational Aspects:

Claire Flanagan (flanaganc@planet.wits.ac.za)

Sarah Buchner (sarah@hartrao.ac.za).

For Theoretical and Computational Aspects:

Fabio Frescura (frescuraf@physics.wits.ac.za)