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1997 SURF Proposal - Stability of Wave-like Pulsar Winds

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Introduction to Pulsars and Relativistic Pulsar Winds

Thirty summers ago radio astronomers at Cambridge University observed a strange source in the heavens transmitting sharp pulses of power with metronomic regularity. This regularity led many to speculate that the source was a beacon constructed by an alien race, and research work in the area blossomed as a consequence.

Today, pulsars are known to be dead stars. The tendency for a star to collapse under gravity is resisted during its lifetime by the burning of hydrogen and helium. However, when the fuel supply is exhausted, gravitational collapse proceeds unhindered until the star is about 20 km across and as dense as the nucleus of an atom. This is what we call a pulsar.

The star spins faster and faster as it collapses (like an iceskater drawing in her arms); pulsars typically rotate once every few milliseconds. Moreover, as the star collapses, its magnetic field is compressed into a smaller volume, making it much more intense - over 15 orders of magnitude stronger than that of the Earth. Along the magnetic poles, a beam of radio waves is emitted. If, like the Earth, the pulsar rotates about a different axis to the magnetic axis, this beam sweeps around like a lighthouse beam and distant observers (us) see a series of pulses.

Electrons and positrons are created in the intense electromagnetic fields near the pulsar's surface. They are then accelerated away from the pulsar by the same fields, forming a highly relativistic outflow. This outflow, called a pulsar wind, is the primary way in which a pulsar loses energy.

The Fourth Dimension of the Pulsar Wind: How does it vary with time?

The traditional view of the pulsar wind is that, like the outflow from our Sun, it is steady-state; its properties at any point (e.g. density, speed) do not change with time. There are three major problems with this view.

a) The gigantic rotating celestial magnet that is the pulsar acts like a dynamo, driving OSCILLATING currents in its wind.

b) The wind contains two energy components, one kinetic, the other electromagnetic. Near the pulsar, the electromagnetic component is believed to dominate the energy flow. From this beginning, steady-state wind theory predicts that the electromagnetic component will also dominate at large distances from the pulsar, where the wind slams into the surrounding nebula. However, observations show that the opposite is true -

kinetic energy dominates at this boundary. This inconsistency is known as the sigma paradox.

c) Recent Hubble Space Telescope (HST) images of the Crab nebula have shown that the Crab pulsar wind is not steady-state. [1,2]

One solution, proposed by Melatos [3] and motivated by point a) above, is that the wind is wave-like (technically, a relativistic plasma wave). In this picture, the electromagnetic fields in the wind plasma and the particlesπ motions are oscillatory, driven at the pulsar's rotation frequency. It has been shown that this wave-like wind resolves the sigma paradox.

<u>Stability of a Wave-like Wind</u>

A viable wind theory must be stable. Firstly, it must be possible to generate the wind despite energy losses of various sorts. Secondly, small perturbations in the wind must gradually die away rather than amplifying themselves and destroying the flow. Previous work [4,5] has shown that intense relativistic plasma waves are unstable under certain circumstances. The aim of this SURF project is to find out whether they are unstable in this context of pulsar winds.

As discussed above, a relativistic plasma wave contains rapidly oscillating (and therefore constantly accelerating) charged particles. An accelerated charge emits electromagnetic radiation. The more extreme the acceleration, the more power is radiated. A rough calculation for the Crab pulsar shows that its intense electromagnetic fields accelerate electrons (or positrons) to relativistic speeds in about seconds, much less than the pulsar-wave period of 33 milliseconds. In this SURF project, we will investigate whether this energy loss is severe enough to prevent wave propagation.

A second possibility, that a small perturbation amplifies and destroys the wave-like wind via plasma instabilities, is the subject of a related 1997 SURF proposal by Caltech student Ronak Bhatt (also to be supervised by Melatos and Phinney).

<u>The Project</u>

We will begin by carrying out simple analytic estimates of the radiative loss rate to identify the key physics in the problem. The theory of radiation from accelerating charges is well known and has been taught in my courses this year.

We will then treat the problem self-consistently. As a particle radiates away energy, its trajectory changes due to the energy loss ("radiation reaction"), and this needs to be taken into account when calculating the energy loss itself! The currents sustaining the relativistic plasma wave are therefore modified with time, either disrupting the wave (bad) or modifying it into a form where the radiation is lessened and the wave can then propagate only weakly damped (good). This will be investigated by adding the Lorentz-Dirac radiation reaction term to the plasma equations describing the wave and solving numerically to find the evolution of the wave with time. The numerical problem involves integrating coupled ordinary differential equations - a standard computational procedure.

Project Objective: By the end of the SURF, we expect to have determined whether or not the wave is destroyed on a timescale less than the pulsar period. The result is of current interest, because the wave model of pulsar winds holds out some hope of explaining several puzzling pulsar phenomena, not least the sigma paradox.

The above calculations will also tell us about the radiation emitted by the wind and observed from Earth. The predictions of the theory will be testable against recent HST images, which show polar jets, moving (i.e. unsteady) wisp-like structures, and mysterious, highly polarised, bright knots in the flow. [1,2] If the wind is shown to be stable, such tests will be important work for the future.

Schedule of Tasks

Introductory reading and revision on pulsar winds and radiation theory (before SURF commences)
Familiarization with wave-like wind theory (2 weeks)
Simple analytic estimates of radiation losses (1 week)
Add radiation reaction term to plasma equations for wave (1 week)
Solve numerically, investigate properties, stability - zero background magnetic field case (4 weeks)
Solve numerically, investigate properties, stability - non-zero background magnetic field case (2 weeks)

References

1) http://www.stsci.edu/pubinfo/PR/96/22.html
2) Hester et al. 1995, Astrophysical Journal, Vol 448, p 240
3) Melatos & Melrose 1996, Monthly Notices of the Royal Astronomical Society, Vol 279, pp1168-1190
4) Arons 1992, Magnetospheric Structure of Rotation-Powered Neutron Stars, IAU Colloquium 128, The Magnetospheric Structure and Emission Mechanisms of Radio Pulsars, ed. J.A.Gil, p56
5) Sweeney & Stewart 1978, Astronomy & Astrophysics, Vol 66, pp 139-153