The Neutron Star Crust and Surface

PROPOSAL

We, Dany Page (UNAM, Mexico), Madappa Prakash (Ohio University, USA), George Pavlov (PSU, USA) and Robert Rutledge (McGill, Canada), propose a five week summer program in 2007 on the physics of neutron star crusts and surfaces at the INT, Seattle. The focus of the program will be on the theoretical interpretation of the growing observations of neutron stars. Summer is preferred as astronomers are available during this time more easily than at other times. The program will benefit immensely from an active participation of observers. For maximum benefit, we propose to hold a week-long workshop on “Observations and Interpretations of Neutron Star Surfaces” during the program. Several key theorists and observers have expressed their keen interest in this program.

SCOPE AND BENEFITS

The neutron star crust and surface constitute an extra-terrestrial laboratory for studying nuclear physics under extreme conditions and, in contrast to the inner core, are domains in which reliable and accurate calculations can be performed within a few years. Recent observations of neutron stars and their properties are beginning to question many aspects of our current understanding and to present serious challenges for theory. The time is thus ripe to foster inter-disciplinary activities between nuclear scientists and relevant astronomers at the INT. As progress in this field depends crucially on collaborative work between theorists and observers, synthesizing neutron star research is immensely beneficial to both communities.

INTRODUCTION

A neutron star has five major regions: the inner and outer cores, the crust, the envelope and the atmosphere/surface. The atmosphere/surface and envelope contain a negligible amount of mass, but play an essential role in shaping the emergent photon spectrum, whereas the envelope crucially influences the transport and release of thermal energy from the star. The crust, extending about 1 to 2 km below the surface, primarily contains nuclei. The dominant nuclei in the crust vary with density, and range from $^{56}$Fe for matter with densities less than about $10^6$ g cm$^{-3}$ to nuclei with mass number $A \sim 200$ but proton fraction $Z/A \sim (0.1 - 0.2)$ near the core-crust interface at density $\rho_{cc} \approx \rho_0/3$, where $\rho_0 = 2.65 \times 10^{14}$ g cm$^{-3}$ is the nuclear equilibrium density. Such extremely neutron-rich nuclei are not observed in the laboratory, but rare-isotope accelerators (RIA) hope to create some of them.

Within the crust, at densities above the neutron drip density, $\rho_{dr} = 4 \times 10^{11}$ g cm$^{-3}$, where the neutron chemical potential is zero, neutrons leak out of nuclei. At densities larger than $\rho_{dr}$ more of the matter resides in the neutron fluid than in nuclei whereas at the core-crust interface, nuclei are so closely packed that they are almost touching. At somewhat lower densities than $\rho_{cc}$, the nuclear lattice can turn inside-out and form a lattice of voids, which is eventually squeezed out at densities near $\rho_{cc}$. If so, beginning at about 0.1$\rho_0$, there could be a continuous change of the dimensionality of matter from 3-D nuclei (meatballs), to 2-D cylindrical nuclei (spaghetti), to 1-D slabs of nuclei interlaid with planar voids (lasagna), to 2-D cylindrical voids (ziti), to 3-Dvoids (ravioli, or Swiss cheese) before an eventual transition to uniform nucleonic matter (sauce). This series of transitions is known as the nuclear pasta and it may encompass up to 50% of the crustal mass.

For temperatures smaller than about 0.1 MeV, the neutron fluid in the crust probably forms a $S_0$ superfluid. Such a superfluid would alter the specific heat and the neutrino emissivities of the crust, thereby affecting how neutron stars cool. The superfluid would also form a reservoir of angular momentum that, being loosely coupled to the crust, could cause pulsar glitch phenomena.

RELEVANCE OF THE CRUST/SURFACE TO OBSERVATIONS

• The radiative properties of the atmosphere/surface determine our ability to measure the surface temperature of a neutron star. Such measurements are essential for comparison with theoretical models of neutron star cooling and also to study the short-term thermal response of the star to sudden energy release, as in pulsar glitches (possibly related to the neutron superfluid) and magnetar crust cracking (presumably produced by the overwhelming tension of the magnetic field on the solid crust). Spectral fits with atmosphere models appear to successfully derive the temperature distribution for young isolated neutron stars ($< 10^5$ yrs), although the observational situation for older isolated neutron stars is less clear.
• The transport properties of the entire crust allow us to deduce the core temperature, which in turn is determined by neutrino emission and baryon pairing at the extreme densities reached in the inner core. Knowledge of the electrical conductivity of the crust is crucial to understand the evolution of the pulsar magnetic fields. Recent observations of cooling of transiently accreting neutron stars, and more importantly of post-burst cooling magnetars, are presently delivering the first constraints on these properties.

• Vortices formed by superfluid neutrons in the inner crust are thought to pin on nuclei and/or lattice defects, and if pulsar glitches are due to their unpinning one can delimit the crustal moment of inertia for which current deductions lie in a narrow range of 4 to 5% of the total. This places strong constraints on the stiffness of the supernuclear equation of state.

• In the case of neutron stars undergoing accretion in a binary system, thermonuclear reactions occurring at the surface induce x-ray bursts. As a result, matter is gradually pushed to higher densities and its composition readjusts through electron capture, neutron emission and absorption, and pycnonuclear reactions. The energy released by these reactions heats up the star whereas the energy produced by the burst at the surface is almost totally radiated away. The amount of heat deposited by the pycnonuclear reactions in the crust depends somewhat on the constituents of the ashes from the surface x-ray bursts.

• In cases with transient accretion (“Soft X-Ray Transients,” SXRT), the hot surface of the star can be directly observed after accretion temporarily ceases. The inferred temperature during quiescence results from a balance between crustal heating, neutrino losses from the core, and radiative losses at the surface. As these accreting neutron stars can be more massive than isolated neutron stars, the opportunity exists to study matter at higher densities than those reached in classical cooling neutron stars. In addition, the short-time thermal response after an accretion phase can give us much information about the transport properties of the crust and the nuclear reactions occurring in the deep layers; observations of this phenomenon are presently taking place.

THEORETICAL ISSUES TO BE ADDRESSED

• At the lowest densities, the surface of the star may be a magnetic solid as proposed more than 30 years ago by Ruderman. Given the failure of atmosphere models in fitting spectra of old cooling neutron stars, a solid magnetic surface is a natural alternative. The composition of this surface is directly related to the formation of the crust. A detailed understanding of thermal emission from these magnetized solids is hence essential for data interpretation. As only crude models have been proposed so far, almost everything remains to be done.

• The chemical composition of the crust has generally been taken to be that of “cold catalyzed matter”. This may not be so even in the case of isolated neutron stars. Fall back and late hypercritical accretion may commonly take place in core-collapse supernovae with subsequent readjustment of the chemical composition as accreted matter is pushed to higher and higher densities. This is similar to what happens in binary systems, but on a much shorter time scale. The evolution of the chemical composition in the presence of accretion will be critically examined.

• To date, the transport properties of the crust have been calculated under the assumption that the crust is a pure crystal. Only rough estimates exist in the case that the impurity content is very high or the matter is amorphous. Theoretical developments to encompass impure crystalline structure will be assessed.

• In the deepest layers, a “pasta” phase is expected to exist. However the details of its layers depend on the nuclear interactions used as even its existence has been questioned. The
structure and energetics of this phase including quantum effects are beginning to be explored and will be reviewed. However, its response, even its survival, to accretion and/or fall back has not been explored and its transport properties have only been roughly estimated. First steps in this direction will be initiated.

• The “pasta” phase is also of relevance in the evolution of core-collapse supernovae as neutrino scattering in this phase is likely an important issue for the redistribution of neutrino energy after shock lift-off. Classical molecular dynamical calculations to determine the structure of and neutrino scattering in this phase have recently been undertaken, but require much refinement to capture quantum effects to which emphasis will be placed.

• In the inner crust, the issue of vortex pinning needs rethinking. The pinning energy per nucleus is still uncertain and it may even be so small that pinning would not occur. The structure of vortices and their motion within the pasta phase is an unexplored area. Recent observations of long time (~ months) periodic variations in pulse arrival time of three isolated pulsars have been interpreted as evidence for free precession, which is incompatible with vortex pinning. If pinning in the crust is ruled out, pulsar glitches must be produced in the core. This would place an important constraint on the supernuclear equation of state.

Suggested Participants (list of names)