THE NEUTRON STAR AS A QUANTUM CRYSTAL

Dr. Vittorio M. Canuto

During the last 8 months I have been studying the structure of the interior of neutron stars in collaboration with Dr. S. M. Chitre, an NAS-NRC Research Associate at the Institute for Space Studies in New York.

This is one of the current concerns in astrophysics for the following reason: Few regions in astronomy have profound and general significance because they have a direct bearing on the validity of the basic physical laws that govern the universe as we know them.

The explanation of these specific areas in astronomy stretches the existing scientific knowledge to its limits and indicates a direction in which we may want to modify the basic laws of nature.

One such area is quasars, seyfert galaxies, and exploding galaxies, with energy releases that are very difficult to explain with any known mechanics or any known kind of forces.

A second area can be defined as the complexity of general relativity, gravitation, and cosmology. A third area is the role of neutrinos in stellar evolution with impact on theories of weak interactions.

The fourth area, which is especially close to me as a former nuclear physicist, is the existence of super-dense states of matter, such as neutron stars, where matter is being squeezed down to such densities (about a billion tons per cubic centimeter) that the particles are less than 10^{-13} cm apart. This is not much more than the size of the particles themselves, and new information about the structure of the elementary particles may result from the computation of the properties of such highly compressed objects and their comparison with the observational data.

Our work has gone into calculating the equation of state for the interior of neutron stars. Now, the interior of neutron stars involves known forces, i.e., nuclear forces, and almost completely unknown forces, such as hyperonic forces. By hyperons I mean the collection of strange particles – lambda, sigma, etc.

The physical principles behind our work are the following. Since the density is so high, the particles are so close together that they only feel a strong repulsion. They repel each other; therefore, it makes sense to think that to minimize the energy the particles would arrange themselves in a very orderly system (as a crystal) instead of being randomly distributed (as in a gas). We therefore computed the energy considering that the system was really a crystal and that the system was a gas. To do that we had to build up the hyperonic nuclear forces. That took at least 50 percent of our work. Now we have a very reliable, good potential. The set of equations that we had to employ was not available at the time because this work was absolutely new in the field of solid state.

Putting the two things together, we arrived at the first conclusion: The lower state of energy is really achieved by arranging these heavy particles in a crystal array.

Figure 1 shows what we have found for densities of 10^{15} g cm^{-3}. The minimum energy is achieved when you arrange neutrons in this way, which is centered cubic lattice. I just want you to recall that cesium chloride crystallizes with this structure.

You see we have neutrons in the corners and the proton in the middle. The arrows indicate the spin. One has to try all the possibilities by moving all of these particles and spin configurations until one finds the minimum energy. This combination appears to minimize the energy up to 10^{15} g cm^{-3}. After that, the body-centered cubic structure switches to face-centered cubic structure (Fig. 2) until 10^{16} g cm^{-3}. We therefore come to the conclusion that a system of strong-interacting particles achieves its minimum energy by arranging the particles in a very orderly crystal.

The conclusion is that the previous computations of the neutron star mass based on a gaseous arrangement of particles are off; there appears to be a new configuration.

CHAIRMAN:

Are there any questions for Dr. Canuto?

MEMBER OF THE AUDIENCE:

Does the crust remain crystallike?

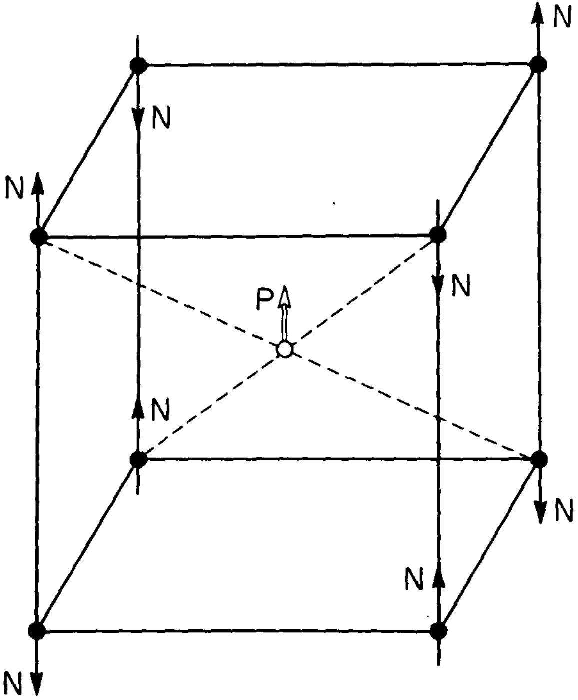

Figure 1–The body-centered cubic crystalline arrangement of protons *P* and neutrons *N*.

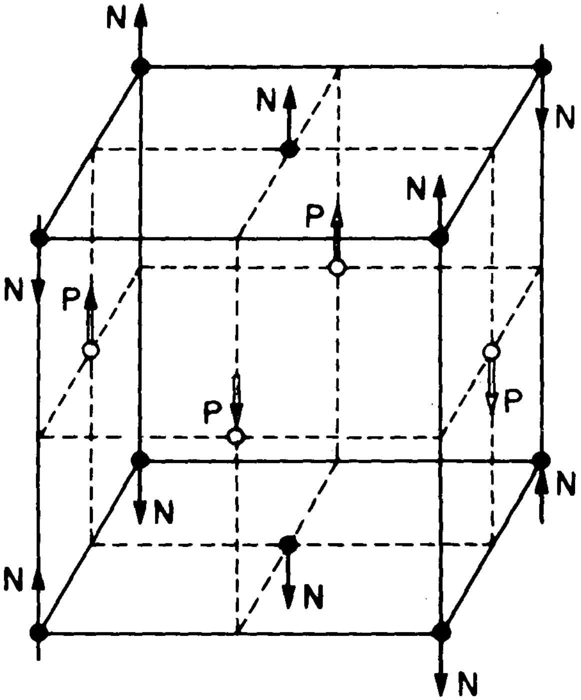

Figure 2–The face-centered cubic crystalline arrangement.

DR. CANUTO:

Sure.

MEMBER OF THE AUDIENCE:

What is in between?

DR. CANUTO:

In between there is probably a layer of superfluid neutrons; at least the density is such that neutrons can become superfluid. This computation refers only to the interior of the star. What goes on when the density is far behind the one we computed, far behind the density of 10^{16} cm^{-3}, is really a mystery since there is no theoretical model on which you can rely to compute anything.

MEMBER OF THE AUDIENCE:

Does the magnetic field affect your computation?

DR. CANUTO:

No. The point is that a magnetic field of the order of 10^{10} T (10^{14} G) in the interior is not affecting the structure because the mass of the protons and the mass of the neutrons are too high to have any effect.

The critical magnetic field is of the order of 10^9 T (10^{13} G) for electrons, and it should be of the order of 10^{16} T (10^{20} G) in order to affect anything. We feel that such a tremendous magnetic field, if it is there, will not change the structure of the solid in any significant way, since the nuclear forces will be dominant.

MEMBER OF THE AUDIENCE:

Have you seen a recent paper on the influence of a magnetic field on neutron stars by M. Ruderman?

DR. CANUTO:

Yes. The magnetic field surely affects many phenomena of a neutron star, mostly the cooling of it, because it affects the energy flowrate out of the star. The magnetic field only affects electrons; it does not affect protons because they are too heavy to be affected by any reasonable value of the magnetic field.