some of the most stringent tests of general relativity, as well as ways of verifying the mechanisms of supernova explosions.

But there is also a reasonable chance that they may provide a means of testing the predictions of the standard model of particle physics, admittedly at the cost of turning experimental physics into observational science.

The density at the core of a neutron star with a mass equal to that of the Sun may exceed 3×10^{18} kg m^{-3}, or 3 billion tonnes per cubic millimetre. The forces responsible for the confinement of this material are the familiar forces of gravitational attraction. But the density is so great that the separation of electrons from their atoms believed to be responsible for the density of white dwarfs is taken a step further: electrons combine with protons in a process which is the inverse of the usual β-decay of the free neutron.

M1, the Crab nebula, is the expanding remnant of a star that was seen to explode almost 1,000 years ago. It now hosts the product of that explosion — a pulsar.

Taken from *A View of the Universe* by D. Malin (Sky Publishing/Cambridge University Press, 1993)

The result is that most of the material in a neutron star with a mass comparable with that of the Sun will consist of free neutrons, mixed with free protons and electrons. A stable neutron star is then prevented from further collapse under self-gravitation by the way in which the nucleons (which are fermions) form a degenerate Fermi gas, exerting an outward pressure. In these extreme conditions, the nucleons are expected to be superfluid — and, in the case of the protons, superconducting.

Like other astrophysical objects, stars and planets for example, neutron stars have a layered structure. Outside the degenerate central region is one in which still intact nuclei are mixed with superfluid neutrons. The outer crust of a neutron star, with a density upwards of 10^{10} kg cm^{-3}, is believed to be essentially a conducting solid. To complicate the physical situation, pulsars appear to have magnetic fields exceeding 10^6 tesla — which is why they are detectable by radio pulses synchronous with their rotation.

Part of the interest of the observable neutron stars is that they are potentially laboratories for the study of a variety of phenomena, not all of them astrophysical. E. Witten, for example, has argued that the inner core of such a star may consist in part of 'quark matter' — a state in which quarks are no longer confined to individual hadron particles.

There have already been speculations in the literature about the geometrical shapes that would be occupied by quark matter in the core of a neutron star. Direct observation of such arrangements will clearly be impossible, but there is a sporting chance that the study of neutron stars over extended periods of time will make it possible to gather an understanding of the properties of neutron matter at high pressures that will be of value in itself, and which will also complement and extend the information that can be gathered from the particle accelerators now likely to be built. Pulsating stars have come to stay. □

How did the Earth form?

THE Galaxy abounds with objects whose nature and origin is poorly understood, from the X-ray binary stars in which mass is being transferred from one to another to the organic molecules accumulating in molecular clouds. Here is a set of problems much closer to home: how did the Earth form, 4,500 million years ago (± 50 million years)?

The question is important not only for its own sake, but because the Earth and the other inner planets are outwardly solid objects, unlike Jupiter and the other much larger objects that lie beyond them; they must therefore have something significant to say about the evolution of the Solar System as a whole, as well as providing a guide in the serious search there will eventually be for habitable planets elsewhere in the Galaxy.

Perhaps significantly, the oldest rocks are dated (by radioactive clocks) to 3.8 billion years. That date fortunately corresponds with that of the second copious wave of meteoritic impacts on the surface of the Moon, one of the few substantial data won by the Apollo programme, suggesting that the Earth accreted a significant but unknown fraction of its mass in the same process.

What was there (or here) before that? There are two lines of evidence — calculations of collapse in the supposed solar nebula and observations of other early star systems. The rarity of the latter accords with what is known of the relative ages of the Sun and the Earth, which suggests that the inner planets were formed within a few hundred million years of the Sun.

The central problem in the formation of any star is the mechanical problem of dispensing with angular momentum during the collapse of a cloud of gas and dust. Calculation and observation agree that the task is usually accomplished either by the formation of a double star or of a planetary disk perpendicular to the axis of the star.

The favoured view of the formation of the inner planets hangs on the condensation of oxides of elements such as iron and silicon in the inner regions of the solar disk. The time course of the evolution of temperature in a collapsing proto-star is not well enough known to reconstruct with confidence the likely course of events during the collapse. Would the temperature in the solar disk have been high enough to vaporize pre-existing dust grains? And what would have been the cement that held together the condensing grains so as to allow them to grow to the solid objects of the order of 1 metre?

The aggregation of planetesimals into more substantial objects the size of planets is another imponderable. It is possible that this process began only when the formation of the giant planets, and Jupiter in particular, provided perturbing forces sufficient to break up into clumps a system of planetary rings much like that now seen around Saturn, with the difference that the constituents were minerals (not ice) and the central object was the Sun.

So is it possible that the second wave of meteoritic impacts on the surface of the Moon 3.8 billion years ago represents the last recorded stage in this enforced aggregation? □