SURFACE COMPOSITION AND COOLING HISTORIES OF NEUTRON STARS

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One of the major questions which has been raised with the rotating neutron star model of pulsars, is whether cosmic rays can be produced by the pulsar phenomenon through the acceleration of the surface material of neutron stars. It is therefore very instructive to review the calculations which have been made on the surface structure and cooling histories of neutron stars.

Figure 1 shows a diagram of the interior of a neutron star, one of a sequence of models calculated by Cohen *et al.* (1970). In this diagram the radii of the various parts of the model are to scale. The total radius of the model is 13.7 km. Over a fairly large range of distance downwards from the surface, ions and electrons also put in an appearance, and below that there is a still narrower strip where protons coexist with the ions, electrons, and neutrons. Below this the ions disappear, and at still greater depths mu mesons put in an appearance. Finally, near the center of the star, the calculations indicated that other hyperons probably appear.

The region containing the ions can be expected to form a crystalline solid, except in the outer fringes of the atmosphere, where thermal effects and the relatively small pressure will vaporize any crystals.

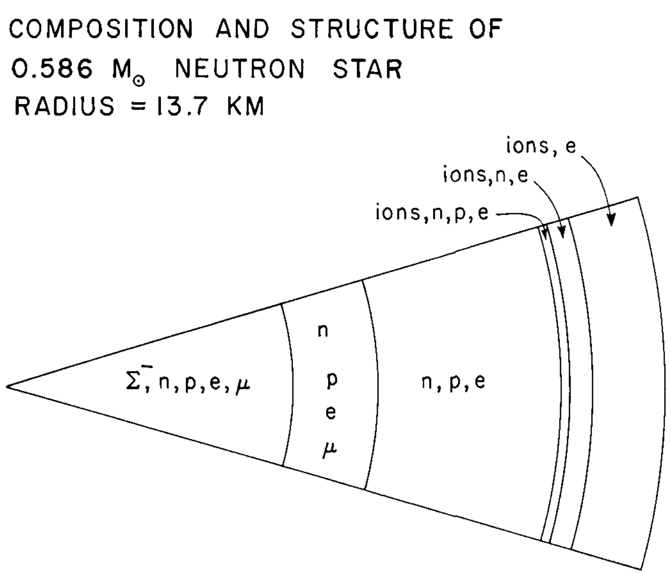

Fig. 1. Composition of the interior of a neutron star.

De Jager (ed.), Highlights of Astronomy, 731–736.

Below the crystalline layer is a region where the neutrons and protons are expected to form superfluids. The protons will corotate with any other charged particles in the presence of magnetic fields, but the superfluid neutrons are expected to interact sufficiently weakly with the superfluid protons, or with the electrons, so that they can be slowed down with the star only as a result of the relatively small friction. Thus the neutrons should be left rotating somewhat more rapidly than the charged particle constituents of the neutron star. The friction which slows down the neutrons also results in a continuous heating of the neutron star interior. One may estimate that in pulsars such as the Crab pulsar or the Vela X pulsar, a surface temperature of the order of 10^6 K is probably required to radiate away the internal heat which is liberated by the friction between the superfluid neutrons and the other particles. This is of some interest in terms of the surface composition.

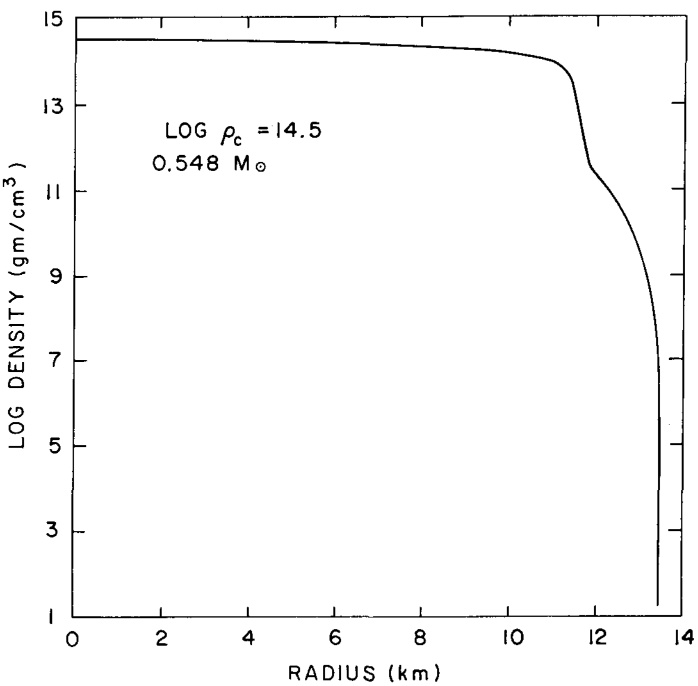

Fig. 2. Density distribution in a typical neutron star.

Figure 2 shows a cross-section of a neutron star of approximately half a solar mass. The density distribution is very flat near the center, but there is a pronounced outward bulge in the surface layers where the composition consists of ions and electrons only.

Figure 3 shows some old calculations made by Miss Tsuruta and myself (Tsuruta and Cameron, 1966) on the cooling of some neutron star models which were computed several years ago. There are two main effects contributing to the cooling. Initially there is neutrino and antineutrino emission by several processes which takes place in the interior of a neutron star. This process dominates the cooling until an age of nearly 10^6 yr. Beyond this point cooling by radiation from the surface dominates.

With our present views of neutron stars and pulsars it is necessary to point out that this diagram is not applicable to the pulsar situation. However, it is instructive to consider the reasons why it is not applicable, and it is also necessary to show these cooling curves because the calculations of the surface composition were based upon cooling curves like these.

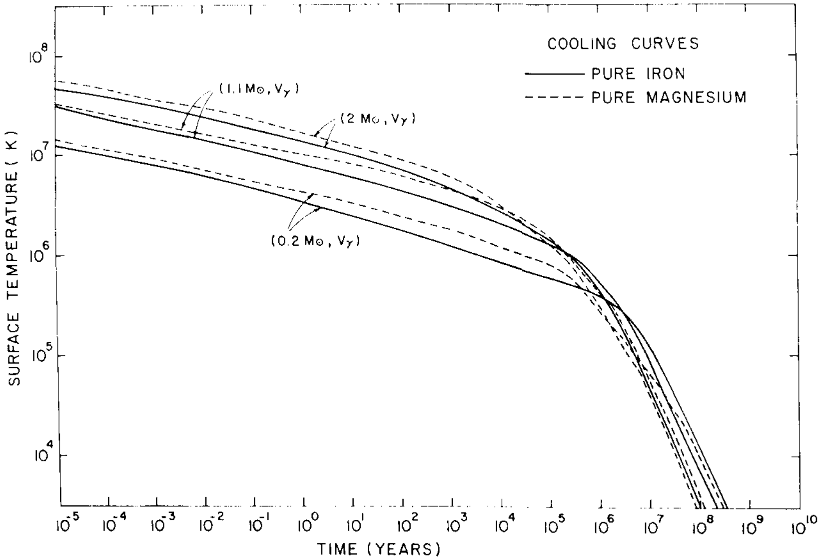

Fig. 3. Cooling histories of several neutron star models as calculated by Tsuruta and Cameron.

One reason why the curves are inapplicable is that no account was taken of superfluidity. Therefore the heat capacity of a star was calculated to be considerably greater than it would be in the presence of superfluidity. The neutrino cooling is for the most part wrong because with superfluidity present there is an energy gap at the Fermi surface of the neutrons and protons. This eliminates a great deal of the phase space which was assumed to be available in the calculation of the neutrino and antineutrino emission from the interior. Therefore some of the neutrino and antineutrino emission processes would be considerably suppressed.

In the presence of a strong magnetic field, the opacity used in the surface layers in this calculation will be incorrect. These old calculations indicated that the ratio of the interior to the surface temperature would lie between a factor of 10 and a factor of 100. At the present time we cannot really estimate what that factor should be.

In the presence of a strong magnetic field, the motion of the electrons perpendicular to the lines of force is quantized. For a nominal magnetic field of about 10^{12} G near the surface of a neutron star, the first available level for the perpendicular motion

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lies at about 10 keV excitation energy. For the most part in these cooling history calculations one deals with surface thermal energies considerably smaller than that.

A photon traversing the surface layers of a neutron star will travel freely if its electric vector lies perpendicular to the magnetic line of force, for then it will be unable to excite an electron to one of the perpendicular states. Hence the opacity for Compton scattering will be extremely small for photon motion along magnetic lines of force and for one state of polarization for travel perpendicular to magnetic lines of force. These effects have recently been calculated by Canuto (private communication).

In the presence of strong magnetic fields, atoms are expected to have their electronic structure deformed, so that the electrons are in *s*-states along the direction of the magnetic lines of force. The excitation of these electrons into a state of the continuum lying along the magnetic field line can only occur if the photons have a component of the electric vector along the magnetic line of force. Hence it can also be expected that bound-free processes will have greatly reduced cross sections along magnetic lines of force. These various considerations might lead one to expect that the net opacity of the surface layers will be considerably reduced relative to the opacities assumed in the earlier cooling history calculation, and hence the ratio of the interior to the surface temperature of a neutron star should be considerably less than previously estimated.

Some time ago (Cameron, 1965) it occurred to me to wonder if the surface composition of a neutron star might be such, that if a neutron star were able to eject a surface layer into the cosmic rays, one would get a composition of the cosmic rays which agreed with the observed heavy element composition. Chiu and Salpeter (1964) published at that time a paper indicating that hydrogen and helium on the surface of a neutron star would quickly diffuse into the interior and be lost. Therefore one of my students, Leonard Rosen, set out to do the diffusion problem somewhat more quantitatively by coupling the diffusion equations for many components near the surface to the nuclear reaction rate equations, so that one could take into account simultaneously the diffusion of several different constituents in the interior of a neutron star and the alteration of the composition of these constituents which takes place as a result of nuclear reactions (Rosen, 1969).

The net result of these calculations was to show that material is very efficiently processed into iron all the way up to the surface. Typically, nearly everything at the surface is in the form of Fe^{56}. Si^{28} is present only at the level of about two percent, and other intermediate nuclei in the transformation chain are much less abundant than the silicon. Thus calculations following the conventional cooling curve predict that the surface layer of a neutron star should be overwhelmingly iron with a very small contamination of silicon. However, the ratio Si^{28}/Fe^{56} for the entire atmosphere is only 2×10^{-11}. The helium abundance is much less than this.

I also had in mind that there would probably be some processes which, in the presence of a magnetic field, would reduce the opacity a great deal. Hence Rosen carried out one other calculation which made an extreme assumption about the cooling.

This calculation assumed that the neutron star cooled isothermally: the central temperature was assumed to extend unchanged all the way to the photosphere. This would be the case if the opacity were to be completely eliminated during the cooling process. Under these circumstances the star cools to 10^6 K in a very short time, of the order of 30 yr, but because of the high temperature near the surface, once again the outer envelope is converted essentially all to iron, with less than 10^{-3} of helium, and small amounts of other elements. However, helium is the predominant constituent of the outer 10^{21} g of the star.

Thus over a wide range of cooling histories the outer envelope is overwhelmingly converted to iron. An intense magnetic field can lead to rapid cooling and to an outer layer predominantly of helium, but the next most abundant constituent even in that layer is iron.

The only other condition that one might think of that could produce a different surface composition for a neutron star would be the infall of material on to the surface of a neutron star. A long-term slow infall of the material seems inconsistent with the general picture that we have of the way in which a pulsar operates; pulsars would almost certainly expel any infalling material. However, immediately after a supernova explosion one might get a reimplosion of some layers in which perhaps, if one were optimistic, there might be a little hydrogen admixed. Material cannot fall back too rapidly, or else the rate of heating of the surface layers by the infall would complete the thermonuclear conversion of the material into iron. If the infall occurred sufficiently after the supernova explosion so that the neutron star had cooled to the point where thermonuclear reactions near the surface had stopped operating, and if the infall rate were small enough so that the surface temperatures stayed too low for thermonuclear reactions, then the hydrogen contained in the infalling material would still be destroyed by pycnonuclear reactions about a meter or so below the photosphere of the star. Thus only a layer near the surface of the star containing perhaps 10^{13} g would be able to preserve its hydrogen under any circumstances. If we gave each particle in 10^{13} g an energy of about 1 GeV and pushed it off into space, then the present energy output of the Crab Nebula would maintain this process only for some 10^{-4} sec, and then one would be down to still lower depths in the neutron star. Thus it certainly seems a safe conclusion that very little hydrogen could be accelerated from a neutron star into space. The great bulk of material ejected from a neutron star should consist of iron, with perhaps a significant amount of helium, and very little of other elements.

Some workers might find it attractive to think that the iron in the cosmic rays could be injected by pulsars. However, not too much iron can be injected in this way, since only about the outer 10^{27} g of a neutron star consists of iron. Below that, the material becomes somewhat more neutron-rich and its mass number is higher than the mass number of iron. At higher densities nuclear statistical equilibrium tends to produce an element of maximum abundance in the vicinity of Ni^{78}, so that after stripping the iron away from a neutron star one would begin to inject nuclei of about mass 78 into the cosmic rays in considerable numbers. The fact that this process has not been observed is therefore perhaps an argument that not too much of a neutron star surface composition can have been injected into the cosmic rays.

Therefore it seems to me that if the pulsars are responsible for the injection of a sizable component of the cosmic rays into the Galaxy, they must do so as a result of an electromagnetic or hydromagnetic interaction with the surrounding ejected nebulosity from the supernova explosion. This ejected nebulosity is likely to be of much more normal composition. Indeed, the main way in which the ejected nebulosity is likely to differ from normal solar composition is also the main way in which the cosmic ray composition differs from the ordinary composition of the Sun.

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