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Maxwell, O.V.

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O.V. Maxwell*

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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*Dept. of Physical Sciences, Florida International University, Tamiami Trail, Miami Florida 33199

Cooling of Neutron Stars with Hyperons

One of the greatest difficulties encountered in the study of neutron stars lies in the connection between the observed properties of the stars and their interior physics. This difficulty is two-fold: on the one hand, measurements associated with the pulsed emission from pulsars and X-ray binaries are sensitive to details of emission and accretion mechanisms and consequently, depend more upon the surface properties of neutron stars than their interior properties. On the other hand, even where a dependence upon interior conditions can be established, this dependence is often masked by other considerations and typically involves just the overall M vs. R relation, which is not particularly sensitive to the detailed composition of the star.

In contrast with pulsed emission phenomena, the possibility of detecting unpulsed blackbody x-rays from neutron star surfaces provides a more direct and fairly sensitive probe of interior conditions. Detection of such radiation allows one to establish a surface temperature for the star (assuming a particular value for the radius), which through solutions of the general relativistic heat transport equations in the crust, provides an estimate of the interior temperature. Because young neutron stars cool primarily by means of neutrino emission from the interior, the latter quantity is rather sensitive to the interior equation of state.

In the past few years the quality of observational information connected with the neutron star cooling problem has greatly improved. A number of compact sources of unpulsed radiation with blackbody spectra have been detected [1]-[3], and through satellite measurements, upper limits on the blackbody fluxes from possible compact sources in several young supernova remnants have been obtained [4], [5]. Recent cooling calculations within the "standard scenario", wherein neutron star interiors are assumed to consist primarily of neutrons with small admixtures of protons, electrons, and muons are consistent with the detected blackbody fluxes, but may not allow cooling rapid enough to accommodate some of the upper limits on fluxes established for compact sources in young supernova remnants [6]-[9]. Thus, if these supernova remnants do indeed contain neutron stars, their observed thermal properties may require departures from the standard scenario. Such departures cannot be too extreme, however; otherwise, the detected blackbody fluxes from compact sources could not be accommodated. If neutron stars contained substantial regions of pion-condensed matter or quark matter, for example, black body surface emission would not be detectable more than a few hours after formation.

One possibility for accelerating the cooling of neutron stars in young supernova remnants, while at the same time accommodating the observed blackbody fluxes from the detected sources, is to allow hyperon admixtures in neutron star matter at sufficiently large densities. Such admixtures can affect the thernal evolution of neutron stars in several ways. In the presence of hyperons, a number of neutrino emission processes, in addition to those occurring in the standard scenario, are possible. If these additional processes are more rapid than the standard scenario processes, cooling will be accelerated. The presence of hyperons also influences the extent of the regions of neutron and proton superfluidity by altering the relative contributions of the nucleons to the total baryon density. The neutron and proton super fluid gaps are strongly dependent on both the absolute nucleon densities through the pairing interactions [10]-[13] and on the relative concentrations of neutrons and protons through the effective masses [10]-[15], which determine the densities of states at the Fermi surfaces. Super fluidity exerts a dual affect on neutron star cooling. On the one hand, by introducing a gap at the Fermi surface, it exponentially reduces the phase space available to final states in neutrino emission processes, thereby retarding the cooling. On the other hand, it also reduces the heat capacity of the star, which accelerates the cooling. Since the interior neutrino emissivities vary as T^8 in the absence of superfluidity while the heat capacity varies linearly with temperature, the first effect predominates at high temperatures (but $T<T_c$) early in the evolution of the star, while the second effect is more important later on. Whether or not the hyperons increase or decrease the extent of the superfluid regions in the star will depend sensitively on the equation of state (i.e., at what densities hyperon admixtures become important) and on the central density of the star.

In view of these considerations, it is proposed that a detailed numerical study of neutron star cooling scenarios in the presence of interior hyperons can be carried out employing the relativistic mean field equation of state discussed in ref. [16]. Neutron stars can be roughly divided into three regions according to their thermal characteristics: a locally isothermal interior composed of a hadronic-leptonic soup, a crust region where most of the baryons are bound in neutron rich nuclei, and the surface. The interior cools primarily by neutrino emission through either URCA type processes,

$$A + B \rightarrow C + B + \bar{\nu} + e^-, \qquad (1)$$

or neutrino pair bremsstrahlung,

$$A + B \rightarrow C + D + \nu + \bar{\nu}, \qquad (2)$$

where A, B, C, and D are baryons. In these processes a strong interaction either prior to or subsequent to the weak interaction permits simultaneous energy and momentum conservation among initial and final particles with different Fermi energies. Quantitative estimates for the associated emissivities may be obtained through a procedure analogous to that described in ref [17], but employing a one-boson-exchange model for the strong interaction and treating the energy-momentum relation explicitly rather than through use of effective masses. In crust region the dominant cooling reaction involves neutrino pair production through an electron-nuclear interaction,

$$e^- + (Z,A) \rightarrow e^- + (Z,A) + \nu + \bar{\nu} \qquad (3)$$

Approximate analytic formulae for the emissivity for this reaction have recently been obtained in refs. [18]-[19]. Finally, the surface of the star cools through emission of blackbody photons.

In principle, determination of the cooling behavior of a neutron star requires the solution of the full set of finite temperature, general relativistic structure equations. Because $kT << E_F$, however, where E_F is a typical Fermi energy in the interior, the gross structure of the neutron star is not affected by its thermal properties and can be treated separately. Moreover, due to the large thermal conductivities of the degenerate particles there, the local temperature in the interior and inner crust regions of the star is nearly constant. Thus, the thermal transport equations need only be integrated through the outermost layers of the star where there is a significant temperature gradient. Rather than accomplishing this directly, it is convenient to employ the results of ref. [20] where an approximate analytic formula is given for the interior temperature in therms of the surface temperature and the surface gravity. With this formula and with explicit expressions for the neutrino emissivities, specific heats, and surface photon luminosity, the luminosity equation can be integrated over the density profile of the star to obtain the surface temperature as a function of time.

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LAWRENCE BERKELEY LABORATORY
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BERKELEY, CALIFORNIA 94720