NEUTRON STAR COOLING: EFFECTS OF ENVELOPE PHYSICS

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ABSTRACT

Neutron star cooling calculations are reported which employ improved physics in the calculation of the temperature drop through the atmosphere. The atmosphere microphysics is discussed briefly. The predicted neutron star surface temperatures, in the interesting interval $300 \leq t\ (\mathrm{yr}) \leq 10^5$, do not differ appreciably from the earlier results of Van Riper and Lamb (1981) for a non-magnetic star; for a magnetic star, the surface temperature is lower than in the previous work. Comparison with observational limits show that an exotic cooling mechanism such as neutrino emission from a pion-condensate or in the presence of percolating quarks, is not required, unless the existence of a neutron star in the Tycho or SN1006 supernova remnants is established.

A neutron star cooling model calculates the evolution of the star's temperature by balancing the energy lost, through volume neutrino emission and surface photon radiation, to the change in the thermal energy of the star. The model assumes the interior ($\rho > 10^{10}$ g cm^{-3}) is isothermal. (See Nomoto and Tsuruta, this volume, for an evolutionary model where the isothermality assumption is relaxed; this model does approach isothermality after several hundred years. The differences between their soft cooling model and our soft cooling model are much greater than the differences between their cooling model and their evolutionary model.) The thermal content of the star depends on the interior temperature T_m. The observable surface temperature T_s is related to T_m by an atmosphere (or envelope) calculation, which solves the coupled equations of atmosphere structure and heat transport by electron conduction and radiation diffusion. The atmosphere integration requires an equation of state, a radiative opacity, and a thermal conductivity. (Each of these microphysics relations is a theoretical construct.)

Previous work (Tsuruta 1979; Glenn and Sutherland 1980; Van Riper and Lamb 1981) has relied on the thermal conductivities

J. Danziger and P. Gorenstein (eds.), Supernova Remnants and their X-Ray Emission, 513–516.

https://doi.org/10.1017/S0074180900034379 Published online by Cambridge University Press

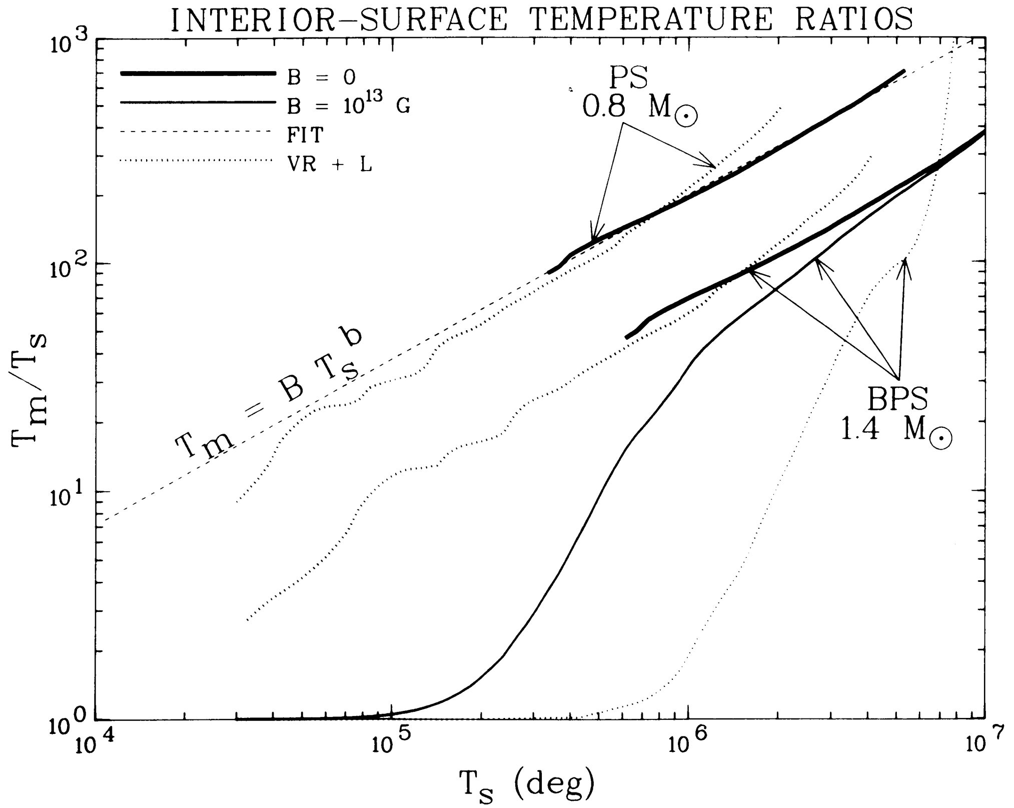

Figure 1. Ratio of the temperature at the edge of the isothermal core T_m to the surface temperature T_s, as a function of the surface temperature. The central temperature T_c is higher than T_m by the ratio of redshifts $e^{\phi m}/e^{\phi c}$. T_s is the local surface temperature, not the apparent temperature $T_\infty = e^{\phi s} T_s$ (T_∞ is the temperature an observer would infer from a thermal spectrum). The solid lines are from the current calculations. The current zero field calculations do not extend below $T_s \approx 2 \times 10^5$ deg because integrations at the lower tempertatures encounter a regime where the (negative) Coulomb correction dominates the total pressure. In the cooling calculations, these atmosphere relations were extrapolated with the slope of the straight dashed line (the extrapolated regions are shown by dashed lines in Fig. 2). The dotted lines are from Van Riper and Lamb (1981). The two curves that reach $T_m/T_s = 1$ are for an atmosphere with a magnetic field $B \approx 10^{13}$ G; the other cases are for B = 0. The dashed line is a first order fit, of the form shown, to the zero field case. A fourth order fit to the (solid) magnetic case has been plotted. The temperature ratios depend only on the neutron star surface gravity $g = GM/[R^2(1-2GM/c^2R)^{\frac{1}{2}}]$. Two extreme cases are shown: A low mass star with a stiff interior equation of state [Pandharipande and Smith (1975)], for which log g = 13.614 (cm s^{-2}), and a soft [Bayn, Pethick, and Sutherland (1971) EOS] star with cannonical mass, for which log g = 14.712.

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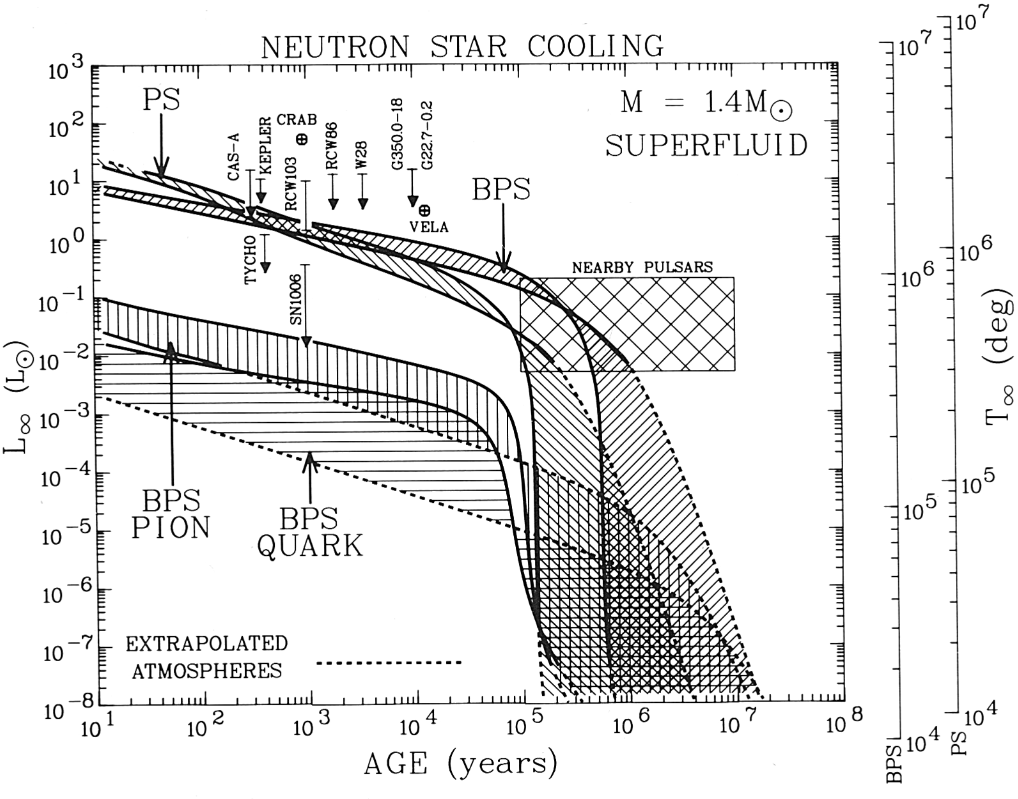

Figure 2. Apparent luminosity L_∞ of cooling neutron stars as a function of the stars age. All cases shown are for a 1.4 $M_\odot$ neutron star with neutron and proton superluidity taken into account. The label "PS" stands for the stiff equation of state of Pandharipande and Smith (1975), while "BPS" stands for the soft EOS of Baym, Pethick, Sutherland (1971). The presence of a pion-condensate (Maxwell, et al 1977) or of percolating quarks (Kiguchi and Sato 1981) results in greatly enhanced neutrino emission and accelerated cooling, as shown. For each case, a shaded region is delimited by two cooling curves, corresponding to a surface magnetic field B ≈ 10^{13} G and to no surface field. In the early, neutrino dominated cooling era ($t < 10_5$ yr, shallow cooling curves) the magnetic curve lies above the B = 0 curve. In this era, the evolution of the interior temperature, which is determined by volume neutrino emission, is independent of the surface field; the displacement of the curves reflects the different T_m/T_s ratio. At later times, surface photon emission is the dominant cooling mechanism. The magnetic curve then lies below the B = 0 curve, reflecting the lower opacities in the former. The experimental data is discussed in the text, and the atmosphere extrapolations are explained in Fig. 1 and its caption.

calculated by Flowers and Itoh (1976). Subsequent calculations of the conductivity by Yakovlev and Urpin (1980), who use a better plasma structure factor, find that the conductivity may differ from the Flowers and Itoh result by as much as a factor of three. The importance of this was first pointed out by Gudmundsson, Pethick, and Epstein (1982). The present calculations use the Yakovlev and Urpin conductivities in (electron) degenerate matter as long as the density $\rho \geq 10^4$ g cm^{-3}. In non-degenerate matter, conductivities calculated from the Hubbard-Lampe (1969) model are used. This leaves, unfortunately, a large region in which the conductivity must be interpolated. The radiative opacity is, as in all recent work, taken from a table supplied by Los Alamos (Huebner, et. al., 1977). This table also contains the Hubbard-Lampe conductivities, an equation of state, and the ionization level of the iron atoms (the atmosphere is assumed to consist solely of this species). Rather than use this equation of state directly, as did Van Riper and Lamb, an equation of state is computed from the number of free eletrons; a coulomb correction to the pressure is included. For stars with a surface magnetic field, the radiative and conductive opacities are multiplied by a correction < 1 (see Tsuruta 1979). A mistake in Van Riper and Lamb's correction has been fixed.

The temperture changes through some represenative atmospheres are shown in Fig. 1. The zero field cases are fit well by $T_m = (T_s/T_b)^b$, where the fitting parameters depend only on the surface gravity g: log T_b = -2.3 log g + 0.2562, b = 0.0022 log g + 1.694. The magnetic cases require a fourth order [log $T_s = \sum_i \log(T_s/s_i)^i$, i=0, 4] fit. Again, the parameters s_i depend only on g. Neutron star cooling curves are shown in fig. 2. The observational points are the same as those shown in Van Riper and Lamb (1981). The Vela point has been displaced slightly to the lower right. The Crab, Vela, and RCW 103 points should be regarded as upper limits to any thermal emission from the neutron star surface. The rectangle characterizes the upper limits that have been obtained for seven nearby pulsars.

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