LA-UR -82-2844

MASTER

CONF-820884--2

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

LA-UR--82-2844

DE83 001941

TITLE: NEUTRON STAR COOLING: EFFECTS OF ENVELOPE PHYSICS

AUTHOR(S): K. Van Ripper, X-7

SUBMITTED TO: IAU Symposium 101 Supernova Remnants and Their X-Ray Emission Conf.
Venice, Italy, August 30 - September 2, 1982

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

NEUTRON STAR COOLING: EFFECTS OF ENVELOPE PHYSICS

Kenneth A. Van Riper
Computational Physics Group
Applied Theoretical Physics Division
Los Alamos National Laboratory
Los Alamos, NM 87545, USA

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 $300 \leq t$ (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 exoctic 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 SNRs 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 emission, 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 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 equivalent opacity for conduction 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 conductive opacities in (electron) degenerate matter as long as the density $\rho \geq 10^4$ g cm^{-3}. In non-degenerate matter, the conductivities calculated in the Hubbard-Lampe (1969) model are used. This leaves, unfortunately, a large region over which the conductive opacity 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 conductive opacities, 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 directly, as in Van Riper and Lamb, an equation of state is computed from the number of free electrons; a coulomb correction 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 temperature changes through some represenative atmospheres are shown in Figure 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: $\log T_b = -2.3 \log g + .2562$, $b = .0022 \log g + 1.694$. The magnetic cases require a fourth order [$\log T_m = \Sigma \log(T_s/s_i)^i, i=0,4$] fit. Again, the parameters s_i depend only on g. Neutron star cooling curves are shown in Figure 2. The observational points are the same as those shown in Van Riper and Lamb (1981). The Crab, Vela, and RCW 103 points should be reguarded as upper limits to an thermal emission from the neutron star surface. The rectangle characterizes the upper limits that have been obtained for seven nearby pulsars.

Baym, G., Pethick, C. J., and Sutherland, P G. 1971, Ap J., 170, p 299.

Flowers, E. G. and Itoh, N. 1976, Ap. J., 206, p 218.

Glenn, G. and Sutherland, P. G. 1980, Ap. J., 239, p 671.

Gudmundsson, E. H., Pethick, C. J., and Epstein, R. I. 1982, Ap. J. (Lett.), 259, p L19.

Hubbard, W. B. andLampe, M. 1969, Ap. J. Suppl., 18, p 297.

Huebner, W. F., Merts, A. L., Magee, N. H. and Argo, M. F. 1977, LA67607, Los Alamos.

Kiguchi, M. and Sato, K. 1981, Prog. Theor. Phys., 66 p 725.

Maxwell, O. V., Brown, G. E., Campbell, D. K., Dashen R. F. and Manassah, J. T. 1977, Ap. J., 216, p 77.

Pandharipande, V. R. and Smit, R. A. 1975, Nucl. Phys. A, 208, p 550.

Tsuruta, S. 1979, Phys. Rept., 56, p 237.

Van Riper, K. A. and Lamb, D. Q. 1981, Ap. J. (Letters), 244, p L13.

Yakovlev, D. G. andUrpin, V. A. 1980, Sov. Astr., 24, p 303.

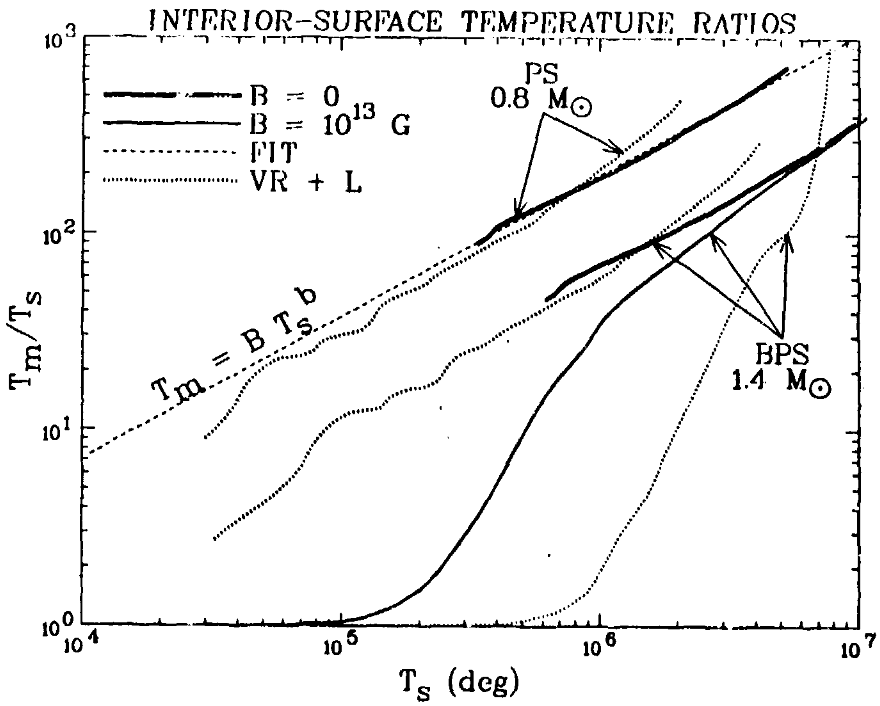

Figure 1 Ratio of the temperature at the edge of the isothermal core T_m to the surface temperature T_s, as a function of the surface temperature. The central temperature T_c is higher than T_m by the ratio of redshifts e^{ϕ_m}/e^{ϕ_c}; T_s is the local surface tempertaure, not the apparent temperature $T_\infty = e^{\phi_s} T_s$ (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 extend below $T_s \approx 2x10_6$ deg because calculations at the lower temperatures 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 Figure 2). The dotted lines are from Van Riper and Lamb (1981). The 2 curves which 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 [Baym, Pethick, and Sutherland (1971) EOS] star with the cannonical mass and $\log g = 14.712$.

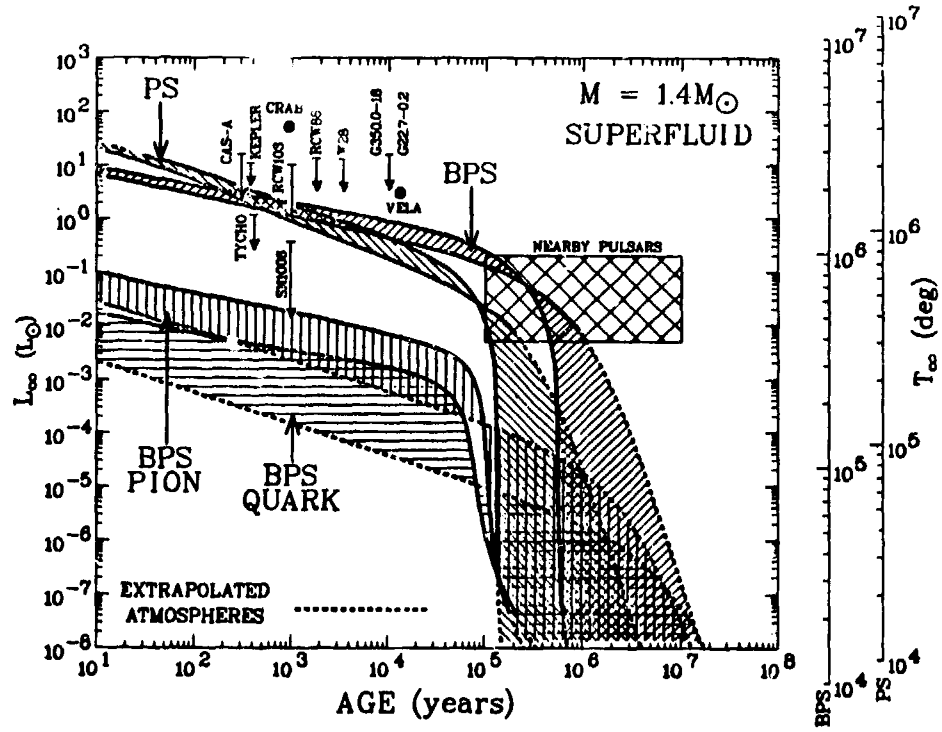

Figure 2. Apparent luminosity $L_\infty = e^{\phi} \cdot L_s$ of cooling neutron stars as a function of the stars age. All cases shown are for a 1.4 $M_\odot$ neutron star with neutron and proton superdluidity taken into account. The label "PS" stands for the stiff equation of state of Pandharipande and Smith (1975), while "BPS" stands for the soft EOS of Baym, Pethick, and 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 difference in 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 Figure 1 and its caption.