THERMAL PROPERTIES OF NEUTRON STARS

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INTRODUCTION

The problem of neutron star thermodynamics has become a rather hot issue during the last one to two years, mainly because the enormous technological improvements brought by the Einstein Observatory (HEAO-B) and the exciting data which have become available to us through this satellite have given us a better hope of testing some of neutron star theories, which may eventually give us invaluable insight into various fields of physics. A somewhat extensive review of the pre-Einstein (Observatory) days was given in Tsuruta (1979a). Since then, many papers, both observational and theoretical, have come out. Most of the observational papers are reports from the Einstein Observatory. Stimulated by such progress on the observational side, various authors of recent theoretical papers attempted to reinvestigate and (or) improve the cooling and heating theories. Dave Helfand (1981) has already given a comprehensive summary of the most recent developments in heating theories. Therefore, in our present report, we shall restrict ourselves to the most recent developments in cooling theories and the comparison with the latest observations. The reader is referred to the earlier reviews (e.g. Tsuruta 1979a,b, 1980a) for the earlier work and the details.

GENERAL BACKGROUND

In our earlier review (Tsuruta 1979a), we reported the results of our up-dated neutron star cooling calculations as of December 1978. Included in these calculations are the general relativistic hydrodynamics, superfluidity, magnetic fields, and the most up-dated neutrino luminosities and photon cooling. Cooling in the presence of pion condensates was also given. In those pre-Einstein (Observatory) days, the only existing observational data were the two rough upper-limits to the surface temperature of the Crab pulsar, first by Wolff et al. (1975) and then by Toor and Seward (1977). We did not include, at that time, the further possible theoretical improvements such as the effects of general relativistic thermodynamics and better opacities, because we

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thought that the uncertainties accompanying the observational values at that time were still far too large as compared with any possible effects of such finer theoretical refinements.

The Einstein Observatory has brought out many surprises, including the determination of the upper limits and possibly the measurement of the surface temperature of some known neutron stars (pulsars) and many neutron star candidates (supernova remnants - SNR's). Therefore, further theoretical investigations have become worthwhile. The further room for possible theoretical improvements was in the following area:

a) The effect of general relativistic thermodynamics,
b) better energy transport theories and opacities,
c) use of the exact stellar evolution code,
d) better work on nuclear forces in neutron star matter,
e) further studies of magnetic effects.

The last two, d) and e), are extremely difficult problems. During the last several months, we have been investigating the first three problems, - namely, a), b), and c). In the following section and in Itoh et al. (1981) we shall give a summary of our findings. A more detailed report shall be given elsewhere (Tsuruta 1980b, Murai et al. 1980). After we have compared our results with observations, we shall briefly compare these results with the latest work by other groups.

RESULTS AND COMPARISON WITH OBSERVATIONS

Our latest theoretical results are summarized in Figure 1. Here we show the photon luminosity as observed at infinity, rather than the stellar temperature, because the latter did not significantly differ from the cooling curves shown in our earlier papers (Tsuruta 1979a, 1980a), and also because the former is more suitable when we compare our theoretical results with observations. We used the ordinary method of neutron star cooling calculations as described e.g. in Tsuruta (1979a), for the "standard" cooling. We adopted the same nuclear models, - namely, the tensor stiff equation of state in our model (B) (= the PS or PPS model in the notation of some other authors) and the Reid-type soft equation of state in our model (A) (= the BPS model by some other authors), in order to see the possible effect of nuclear forces. The lower boundaries to the shaded regions (A) and (B) correspond to the zero magnetic field case, and the upper boundaries correspond to the case with $H = 5 \times 10^{12}$ Gauss. The stellar mass is fixed at 1.3 $M_\odot$. It is generally agreed that these values of mass and magnetic field are representative values which are supported both by theory and observations. It turns out that a neutron star with zero magnetic field generally cools faster without superfluid particles during the earlier periods, while it cools faster in the presence of superfluid particles during the later periods. Therefore, the lower boundaries correspond to the normal (non-superfluid) stars during the earlier periods, while they correspond to superfluid stars in the later periods.

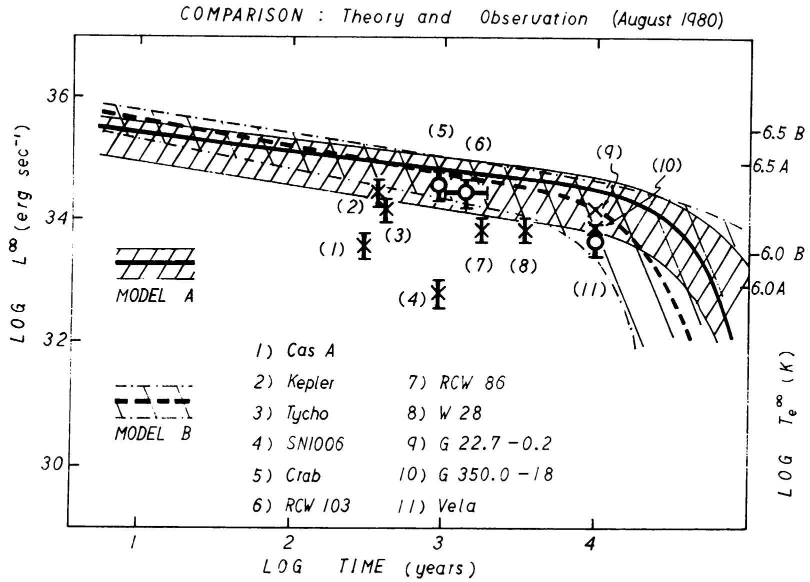

Figure 1. Cooling of Neutron Stars (see the text)

In order to determine the upper boundaries, we took into account the possible effect of uncertainties inherent in the theory of effective masses, their effect on superfluid energy gaps and neutrino luminosities, and the magnetic effects. The reader is referred to our earlier review (Tsuruta 1979a) and the paper by Maxwell (1979) for the details of how we estimated the limits of such uncertainties. By converting back the luminosity at infinity to temperatures, we shall see clearly that there are no significant changes between our earlier results (Tsuruta 1979a, 1980a) and the present ones, during the critical periods of ∿ 100 - 10,000 years. (Note that we showed the local surface temperature at the star in Tsuruta (1979a) and the surface temperature as observed at infinity in Tsuruta (1980a).) The conclusions are:

1. The effect of gravitational redshifts - Due to gravitational redshifts, the surface temperature as observed at infinity is about a factor of 1.5 lower than the true surface temperature at the star for model (A), while this factor is only ∿ 1.2 for model (B).

2. Effect of general relativity on the energy transport and energy balance (see Thorne 1966, 1977) - Through extensive computer calculations, we could confirm our earlier prediction that this effect is negligible both for model (A) and (B), as compared with other more serious uncertainties, such as those inherent in the theories of effective masses, energy transport, magnetic fields, and superfluidity.

3. The effect of better energy transport theories and opacities - In our earlier work, we used the older version of the Cox's opacity table with irons, and the effect of degeneracy on the conductive opacity was not taken into account. Our present results were obtained by using the most up-dated LASL opacity code and the thermal conductivity in the degenerate matter as given by Flowers and Itoh (1976, 1979). By so

doing, we saw some significant changes in the cooling curves during the earlier periods of t < $\sim$ 100 years and the later periods of t > $\sim$ 10^4 years. However, during the critical periods of $\sim$ 100 - 10^4 years, this effect was insignificant (see Tsuruta (1980b) for the details and the reasons). We should note that this is the critical period for our present purpose, because we have the best hope of testing cooling theories during this period. During the earlier period, the conventional method of cooling calculations is not reliable, because the star may not have reached thermal equilibrium (Ray 1979, Itoh et al. 1981, etc.) during these early periods. (Also, no neutron stars have been found which are so young.) When t > $\sim$ 10^4 years, heating must be more dominant than cooling if a neutron star is to be observed (Tsuruta 1979b, Helfand 1981, etc.).

In Figure 1, we compare our present theoretical results with the latest Einstein observations. The observed upper limits (to photon luminosities at infinity) are indicated by the crosses (Murray et al. 1979, Pye et al. 1980, Helfand et al. 1980). We used a circle when the HEAO-B detection may refer to the measurement of the surface temperature (Fabbiano 1980, Harnden et al. 1979a,b, Tuohy and Garmire 1980). The error bars accompanying these observed points include mostly the uncertainties in interstellar absorption. Pulsars have been discovered in the Crab (the source (5)) and the Vela (the source (11)). The other sources are SNR's which may or may not contain neutron stars. However, if we tentatively assume that all SNR's contain neutron stars, our conclusions can be summarized as follows:

1. For some SNR's (e.g. SN1006, Cas A), the observed upper limit is too low to be consistent with the "standard" cooling - the same conclusion as the earlier one (Tsuruta 1980a). (By "standard" cooling we generally mean cooling without the presence of such exotic particles as pion condensates and quarks. We should emphasize that the presence of a neutron star is of course assumed in the definition.) The above conclusion naturally leads to the following possibilities: a) there are no neutron stars in these SNR's, and b) these are pion or quark stars. It was already shown (e.g. Tsuruta 1979a, 1980a) that pion cooling is entirely consistent with the above observational data. Cooling of quark stars was studied by Iwamoto (1980), van Riper and Lamb (1980). They report that it is at least as fast as pion cooling. If the possibility a) turns out to be the case, that may give an interesting effect on our current theories of pulsar formation (e.g. Helfand et al. 1980, Taylor and Manchester 1977, Tsuruta 1979a). If b) is the case, that may give us useful handle on some of the problems in particle and nuclear physics.

2. It is most likely that the observed values for the Crab, Vela and RCW 103 are the actual surface temperatures. We note that these points are all within the shaded regions. That is, all these observed values (the circles) are entirely consistent with the "standard" cooling alone, and we do not require any additional mechanisms such as extra heating and non-thermal mechanisms - contrary to the report by van Riper and Lamb (1980).

3. At the moment it seems that we still have too many uncertain parameters - mass, magnetic field, critical pion density, etc. However, if through further theoretical and observational progress these parameters are better fixed, we may very well be able to distinguish between different equations of state and hence nuclear models. (See Tsuruta (1980b) for the details.) We are aware that some of the readers may feel that we are overly optimistic. However, if we recall the recent history of astrophysics, it is our impression that optimists very often fared well. For instance, who did imagine, say 15 years ago, that a neutron star could ever be discovered?

BRIEF COMPARISON WITH OTHER THEORETICAL WORK

In our recent paper (Tsuruta 1979a, 1980a), we have already compared the theoretical results by the different groups as of October 1979. Therefore, we refer to the above references for the details of these earlier studies. The conclusion was that qualitatively they generally agree well with each other, and the purpose of these earlier (pre-Einstein) papers was at most qualitative in nature.

Two new papers have come to our attention since then, one by Glen and Sutherland (1980) and the other by van Riper and Lamb (1980). For various reasons, we postpone our comments on the latter paper until another occasion (Tsuruta 1980b). The improvements made by Glen and Sutherland (1980) are in the same area as ours, namely a) and b) as listed in an earlier section. We can make relevant comparisons, however, only for the zero field case in the absence of superfluidity. There are still a large number of uncertainties in the theories of the properties of matter in high magnetic fields, effective masses, and superfluidity. Therefore, the estimates of their effects are somewhat subject to personal opinions. For the zero field case with no superfluidity and for $M = 1 - 1.4\ M_\odot$, the results of Glen and Sutherland (1980) and ours agree remarkably well, both for model (A) (their BPS model) and model (B) (their PPS model). More detailed comparisons will be given elsewhere (Tsuruta 1980b).

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DISCUSSION

F.G. SMITH: Does the magnetic field cause a temperature difference between pole and equator, and would this be observable as a modulation of the X-ray flux?

TSURUTA: This depends (a) on the component $\kappa_{\perp}$ of opacity perpendicular to the magnetic field H and (b) on the question whether the surface is in the gas phase or in the solid (liquid) phase. To (a): If $\kappa_{\perp} >> \kappa_{\parallel}$ one may expect an anisotropic distribution of the surface temperature. We have good estimates of $\kappa_{\parallel}(H)$, but unfortunately no reliable work has yet been done for $\kappa_{\perp}(H)$, especially if the surface is in the form of a metal (solid or liquid). To (b): We do not know the answer, if the surface is in the solid or liquid state. If the surface is in the gas phase, one expects the poles to be much hotter than the equatorial plane and one would see a pencil beam shaped radiation from the surface. The fact that we do not detect such pulsed thermal radiation may mean that the surface is already in the form of a metal (solid or liquid) even for young pulsars (e.g. the Vela pulsar).