NEUTRON STAR COOLING: CRITICICAL TEST OF DENSE MATTER PHYSICS

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ABSTRACT

Recent developments in the standard theory of neutron star cooling is critically reviewed. Emphasis is placed on the recent developments in the calculations of thermal conductivity and neutrino energy loss rates.

1. INTRODUCTION

Comparison of the neutron star cooling theory with the results of the X-ray obsevations provides us with an ideal test of dense matter physics. In this paper I will critically review the neutron star cooling and report on the state-of-the-art calculations.

The Einstein Observatory was launched in 1979 and offered the first opportunity for possible detection of thermal radiation directly coming from neutron star surfaces. Most of the analysis is now completed(Tuohy and Garmire 1980; Pye et al. 1981; Heefand 1981; Harnden and Seward 1984; Harnden et al. 1985).

On the theoretical side progress has been made in recent years concerning the calculations of the thermal conductivity of dense matter(Yakovlev and Urpin 1980; Itoh et al. 1983; Mitake, Ichimaru, and Itoh 1984; Itoh et al. 1984c) and neutrino energy loss rates involving electrons(Itoh and Kohyama 1983; Itoh et al. 1984d; Itoh et al. 1984a; Itoh et al. 1984b; Munakata, Kohyama, and Itoh 1985, 1986). In additon to these standard cooling mechanisms it is possible that neutron stars cool off rapidly due to the efficient neutrino emission in the presence of the pion condensate or the quark matter(Tsuruta 1985) or due to the emission of axions (Iwamoto 1984; Raffelt 1985; Kohyama, Nakagawa, and Itoh 1986).

Nomoto and Tsuruta(1986) have recently carried out the standard neutron star cooling calculation incorporating the recent theoretical developments and compared with the results of the X-ray observations. In this paper I will focus on the

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recent developments in the standard(non-exotic) cooling model. Our strategy is as follows: We first work on the standard cooling theory and compare the results with the X-ray observations. If there exist irreconcilable discrepancies, then we introduce exotic cooling mechanisms.

The present paper is organized as follows: Comparison of the cooling calculations with the X-ray obsevations is made in §2. Recent developments in the calculations of the thermal conductivity of dense matter are reviewed in §3. Recent developments in the calculations of the neutrino energy loss rates are reviewed in §4. Concluding remarks are given in §5.

2. COMPARISON OF COOLING CALCULATIONS WITH OBSERVATIONS

In Figure 1 I show Nomoto and Tsuruta's(1986) result on the comparison of the cooling calculations with the observations. According to Nomoto and Tsuruta it is likely that no neutron stars are left in Tycho and SN1006 as Type I supernova explosions may very well have disrupted the stars completely. On the other hand Seward(1987) has pointed out in this Symposium the possibility that a neutron star is hidden in Cas A. In that case Cas A and Vela pulsar are much cooler than the standard cooling theory predicts whereas the other sources are not inconsistent with the standard cooling theory. However, one should note that no definitive obsevation of the neutron star surface temperature has been so far made because of the complete lack of the spectral obsevation.

It is possible that exotic fast cooling mechanisms such as pion condensate, quark matter, and /or axion cooling are responsible for the fast cooling of Cas A and Vela pulsar.

3. THERMAL CONDUCTIVITY OF DENSE MATTER

Thermal conductivity of the dense matter plays an essential rele in the cooling of neutron stars. There has been recent progress in the calculation of the thermal conductivity relevant to neutron stars. Flowers and Itoh(1976, 1979) presented detailed results of the extensive calculations of the transport properties of dense matter. More recently Yakovlev and Urpin(1980) improved upon the Flowers-Itoh conductivity, and presented more accurate results. Their paper marked the beginning of the precision calculations of the elementary processes occurring inside neutron stars. Stimulated by their work Itoh and his collaborators embarked on further accurate calculations of the electrical and thermal conductivities of the dense matter and published the results recently(Itoh et al. 1983; Mitake, Ichimaru, and Itoh 1984; Itoh et al. 1984c).

In this section I will briefly summarize the calculation of the thermal conductivity of dense matter in the liquid phase. At high densities the polarizability of the degenerate electrons can be neglected as a first approximation, and

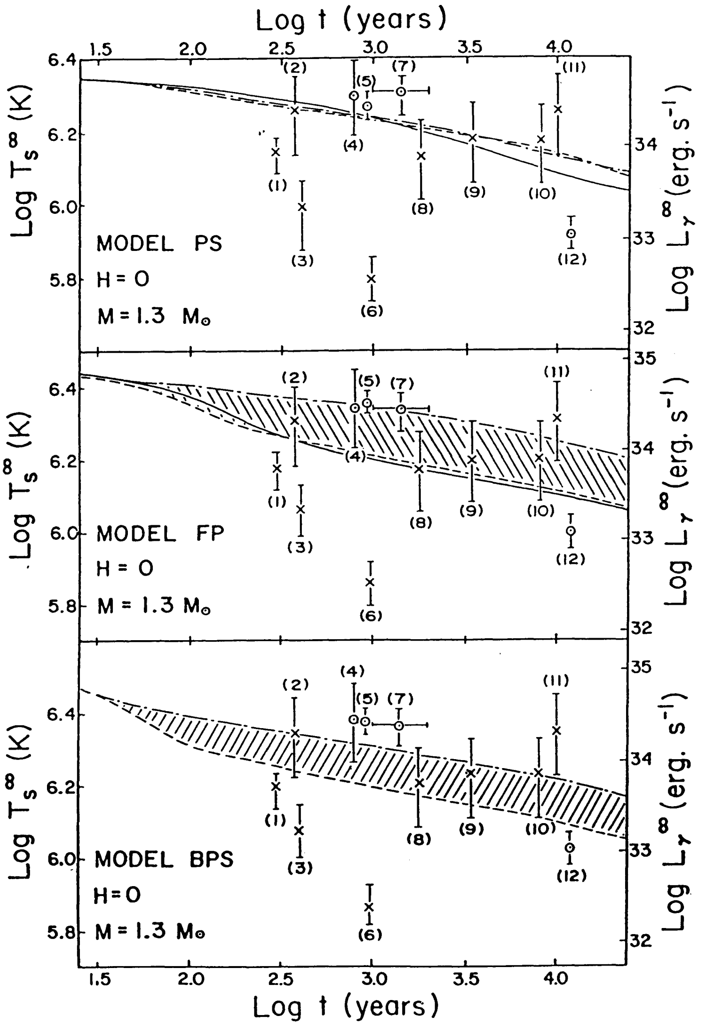

FIG.1. Comparison between the temperature upper limits set by the Einstein observations and the latest theoretical models of neutron star "standard" cooling obtained with the "exact" method. Surface temperatures(left) and photon luminosities(right), both to be observed at infinity, are shown as a function of age, for models PS(top), FP(middle), and BPS(bottom), with $M_A = 1.4M_\odot$ and H = 0. In the dashed curves all standard neutrino emissivities are included. Dot-dashed and solid curves show the maximum and the "best guess" effect of superfluidity, respectively. The numbers refer to the ollowing sources: (1)Cas A, (2)Kepler, (3)Tycho, (4)3C58, (5)Crab, (6)SN1006, (7)RCW 103, (8)RCW86,(9)W28, (10)G350.0-18, (11)G22.7-0.2, and (12)Vela. The circles and crosses refer, respectively, to the temperature upper limits for SNRs with and without detected point sources. The error bars indicate the uncertainty in these upper limits due mainly to the interstellar absorption.

the dense matter can be described as a classical one-component plasma(OCP) embedded in the negative background of electrons. Crystallization of OCP is given by the condition (Slattery, Doolen, and DeWitt 1982)

$$\Gamma \equiv \frac{Z^2e^2}{ak_BT} = 2.275\times10^{-1}\frac{Z^2}{T_8}\left(\frac{\rho_6}{A}\right)^{1/3} \geqq 178, \qquad (1)$$

$$a \equiv [3/(4\pi n_i)]^{1/3}, \qquad (2)$$

where Ze is the ionic charge, T_8 is the temperature measured in units of 10^8 K, ρ_6 is the mass density in units of 10^6 gcm^{-3}, and n_i is the number density of ions. Therefore the liquid state of OCP corresponds to the condition $\Gamma<178$. The ionic correlation in the liquid phase crucially decides the thermal conductivity. In order to incorporate the ionic correlation effect in the calculation of the thermal conductivity, one uses the liquid structure factor of OCP. In Figures 2 and 3 I show the results of the calculation. The ordinate shows a quantity which is proportional to thermal resistivity. Yakovlev and Urpin(1980) completely neglected the effects of electron screening. This accounts for the most part of the discrepancy between their calculation and that of Itoh et al.(1983). In the recent calculations of Itoh and his collaborators accuracy of about 10% is aimed at.

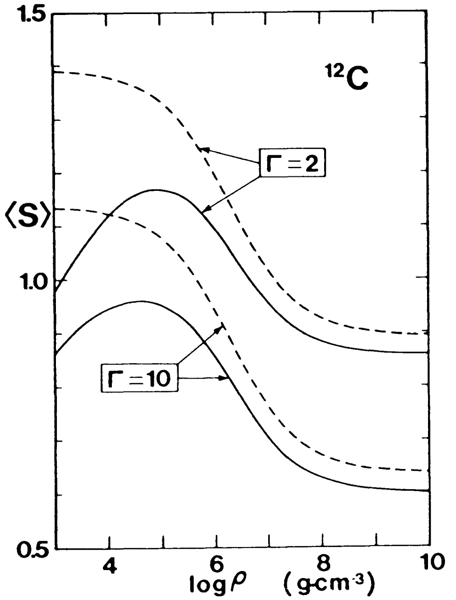

FIG.2. Comparison of Yakovlev and Urpin's resistivity(dashed curves) with the present results(solid curves) for the ^{12}C matter.

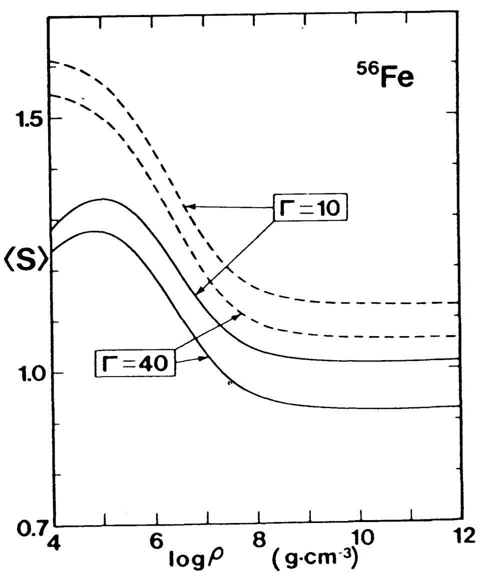

FIG.3. Comparison of Yakovlev and Urpin's resistivity(dashed curves) with present results(solid curves) for the ^{56}Fe matter.

4. NEUTRINO ENERGY LOSS RATES

Neutrino emission processes are efficient cooling mechanisms for neutron stars. There have been important developments in recent years in the calculations of the neutrino energy loss processes involving electrons. There are four major neutrino emission porocesses involving electrons. They are pair, photo-, plasma, and bremsstrahlung neutrino processes. Concerning the former three processes Beaudet, Petrosian, and Salpeter(1967) presented the detailed results of the calculation based on the Feynman-Gell-Mann(1958) theory. More recently Dicus(1972) recalculated these three processes using the Weinberg-Salam theory(Weinberg 1967; Salam 1968). However his numerical calculation was carried out for special densities and temperatures, and hence his results were of little use for stellar evolution computations. Therefore Beaudet, Petrosian, and Salpeter's results were still widely used in stellar evolution computations until recently.

In order to remedy this unsatisfactory situation Munakata, Kohyama, and Itoh (1985, 1986) carried out the calculation of the neutrino energy loss rates due to pair, photo-, and plasma neutrino processes using the Weinberg-Salam theory, and presented detailed results for a wide range of densities and temperatures. In Figure 4 I show an example of the results of the calculation. The results of Munakata, Kohyama, and Itoh's(1985, 1986) calculation are summarized in the following way. Let n be the number of neutrino species other than electron neutrino whose mass is negligible compared with kT. Let Q_{MIK} and Q_{BPS} denote the neutrino energy loss rates calculated by Munakata, Kohyama, and Itoh(1985,1986) and by Beaudet, Petrosian, and Salpeter(1967), respectivly. Then for n = 0 one has $0.35 \lesssim Q_{MKI}/Q_{BPS} \lesssim 0.87$ corresponding to various densities and temperatures; for n = 1 one has $0.56 \lesssim Q_{MKI}/Q_{BPS} \lesssim 0.88$; for n = 2 one has $0.77 \lesssim Q_{MKI}/Q_{BPS} \lesssim 0.88$.

Concerning bremsstrahlung neutrino process Festa and Rudreman(1969) calculated the neutrino energy loss rate using the Feynman-Gell-Mann theory. More recently Dicus, Kolb, Schramm, and Tubbs(1976) calculated this process using the Weinberg -Salam theory. However they did not take into account the ionic correlation effect correctly. Therefore from the point of view of quantitative applications their result was not reliable.

Itoh and his collaborators(Itoh and Kohyama 1983; Itoh et al. 1984d; Itoh et al. 1984a; Itoh et al. 1984b) solved this unsatisfactory situation by calculating the bremsstrahlung neutrino energy loss rate using the Weinberg-Salam theory and taking into account the ionic correlation effects both in the liquid phase and crystalline phase accurately. In Figure 5 I show an example of the results of the calculation. The top curve corresponds to the neutrino energy loss rate that does not take into account the ionic correlation effects and coincides with the result of Dicus, Kolb, Schramm, and Tubbs(1976). The lower curves correspond to the results of the calculation which takes into account the ionic correlation effects accurately. It is readily seen that the ionic correlation effects reduce the neutrino energy loss rate by a factor $\sim$ 3 near the crystallization temperature in the case of ^{56}Fe . Therefore the ionic correlation effects are important factors that decide the quantitative feature of the bremsstrahlung neutrino energy loss rate.

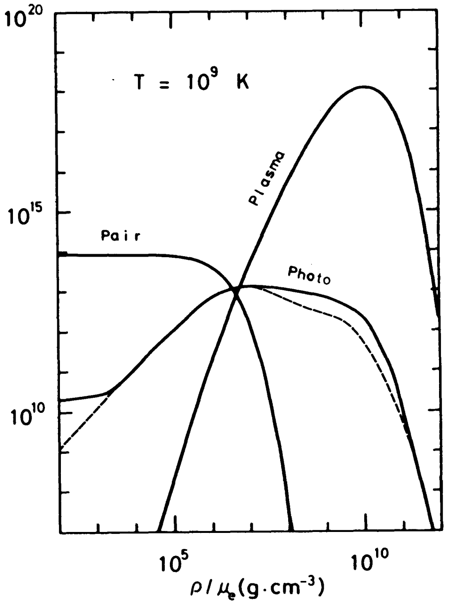

FIG.4. Neutrino energy loss rates Q_{pair}^+, Q_{photo}^+, and Q_{plasma}^{BPS} in erg s^{-1} cm^{-3} as functions of density. (For the definitions of Q_{pair}^+, Q_{photo}^+, and Q_{plasma}^{BPS} see Munakata, Kohyama, and Itoh(1985).)

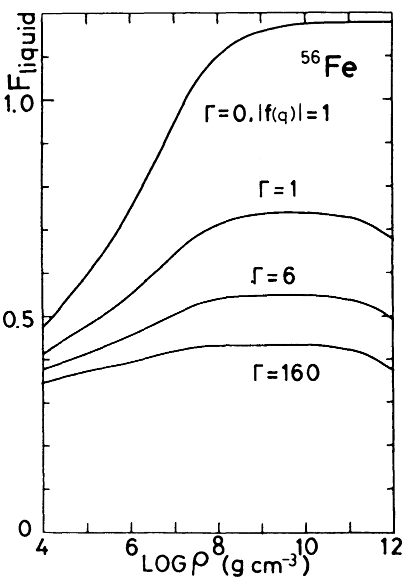

FIG.5. Bremsstrahlung neutrino energy loss rate for ^{56}Fe matter in the liquid metal phase. F_{liquid} is proportional to the neutrino energy loss rate.

5. CONCLUDING REMARKS

As reviewed in this paper remarkable progress has been made in recent years on theoretical studies of neutron star cooling. In order to have more crucial test of the neutron star cooling theory we certainly need more accurate observations of the neutron star surface temperature, especially the observations of the X-ray spectrum coming from the neutron star surface.

To conclude this review paper, I wish to quote a poem of Fujiwara-no-Teika (1162-1241). In his famous diary Meigetsu-ki he cites an old Japanese record of the Crab supernova(1054). It is also interesting to note that Meigetsu-ki was the very record that opened up the modern research on the historical records of supernovae. In this way Fujiwara-no-Teika contributed greatly to the modern study of neutron stars. His poem is:

I wait and wait
For a lady I love to see
My heart getting scorched
Like salt on the seashore burnt

My conclusion is:

I wait and wait
For a neutron star I love to see
My heart getting scorched
Like salt on the seashore burnt

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DISCUSSION

T. Lu: Your calculation seems to be sensitive to the number of neutrino flavors. Could the present cooling data be used to set a meaningful upper limit on the number of neutrino flavors?

N. Itoh: No. The X-ray observational data is not accurate enough to decide the number of neutrino flavors.

A. Burrows: It should be pointed out that it is the modified URCA process that dominates the neutrino cooling of a standard neutron star, not the pair, plasmon, bremsstrahlung, or photo-neutrino processes.

N. Itoh: Of course the modified URCA process is very important. But plasmon and bremsstrahlung neutrinos are also important for neutron stars which have extended envelopes.

A. Burrows: To truly identify surface emission from a neutron star, obtaining X-ray spectra will be crucial. Can you please summarize the status of neutron star emissivity calculations?

N. Itoh: The importance of the emissivity of the neutron star surface has been pointed out by Itoh and Brinkmann. But it is a very difficult problem involving the physics of matter under strong magnetic fields and also the atmosphere.

R. Narayan: With respect to A. Burrows' question concerning the spectrum of X-rays emitted by a hot neutron star, I should mention that there is a poster that I have put up on this subject, describing work by Romani, Blandford and Hernquist. (The authors were unfortunately unable to come to this meeting.) Could you comment on how the conductivity results would be modified if there were magnetic-field-induced anisotropy in the neutron star interior?

N. Itoh: According to the work of Hernquist and his collaborators, the effects of the magnetic field on thermal conduction due to degenerate electrons would not be very great.