EVOLUTION OF NEUTRON STARS IN YOUNG SUPERNOVA REMNANTS

K. Nomoto$^{(+)}$ and S. Tsuruta$^{(++)}$
Max-Planck-Institut für Physik und Astrophysik,
Garching bei München, West Germany

The exciting observational developments in recent years (see Seward, Helfand, Harnden, Becker, etc., in this volume) have made it worthwhile to reexamine neutron star cooling theories. Here we shall give an intermediate report on our work.

PHYSICAL INPUT

The basic stellar structure equations we used are the fully general relativistic version by Thorne (1977). These equations have been solved in the manner described by Nomoto and Tsuruta (1981, 1982), using the same physical input. In order to see the effect of nuclear interactions in the central core, we chose (i) a stiff equation of state by Pandharipande and Smith (1975) called PS model and (ii) a soft equation of state of Reid type called BPS model (Baym, Pethick and Sutherland 1971), because they give boundaries to relatively "realistic" equations of state. The neutrino emissivities included are: modified Urca, neutron-neutron and neutron-proton bremsstrahlung, electron-ion bremsstrahlung, and plasmon, pair and photo-neutrino emissions. The table by Huebner et. al. (1977) was used for radiative opacity and the work of Flowers and Itoh (1976) for conductive opacity.

RESULTS

Typical cooling curves for a stiff model are shown in Figure 1. The gravitational mass $M_G = 1.3M_\odot$, central density $\rho^c = 4.0 \times 10^{14}$ gm cm^{-3}, and radius R = 16.0 km.

Recently the work of Flowers and Itoh was criticised by Yakovlev and Urpin (1980). We carried out envelope calculations by using both the conductive opacity of Yakovlev-Urpin (κ_c(YU)) and that of Flowers-Itoh (κ_c(FI)). Our results are shown in Figure 2. T_b is the temperature at the boundary of the isothermal core and T_e is the surface temperature. (Here we assumed that the isothermal state has been reached already.) We set the surface gravity $g_s = 10^{14}$ cm sec^{-2}, which corresponds roughly to PS model. The solid curve refers to κ_c(FI) while the dashed curve is for κ_c(YU). We note that the difference is negligible. It is somewhat larger as g_s increases, but it is less than a factor of $\sim$1.2 in cases of our interest ($\sim$100 - 10^4 years).

(+) On leave from Department of Earth Science and Astronomy, University of Tokyo

(++) On leave from Department of Physics, Montana State University

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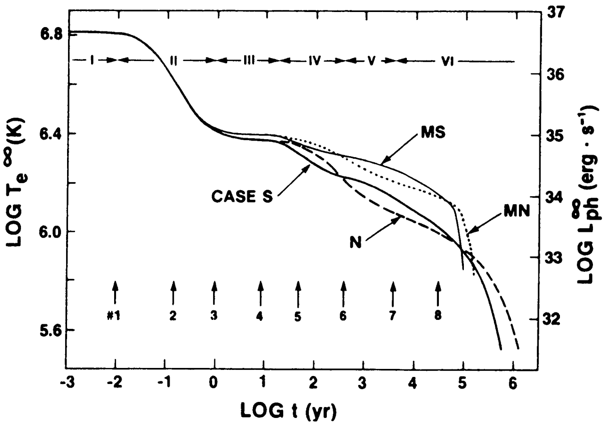

Fig. 1

The surface temperature T_e^∞ (left) and photon luminosity L_{ph}^∞ (right) as a function of t (all measured at infinity), for PS model. The surface magnetic field H = 0 for Case N (no superfluid) and Case S (with superfluid); and H = 5 x 10^{12} gauss for Case MN (no superfluid) and Case MS (with superfluid).

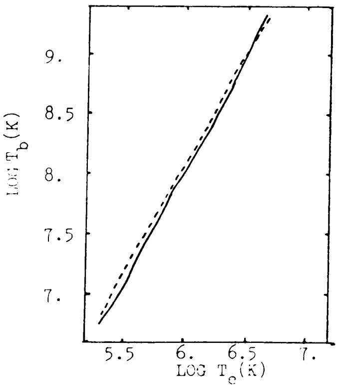

Fig. 2

T_b vs T_e (both local)

Some characteristics of compact sources in young supernova remnants (SNR's) are shown in Table 1 (see reports by Seward, Helfand, Harnden, Becker, etc., in this volume). The names of SNR's are shown in the first column. The next three columns give the estimated distances, diameters and ages whenever known. Point sources are detected in six of these SNR's, which are marked as (*). For these sources, the last column gives the surface temperature (observed at infinity) assuming that all of the non-pulsed portion of the point source radiation comes from the neutron star surface. For the other sources, the last column gives the 3σ level upper limits to the surface temperature. These values are obtained by assuming blackbody radiation and for R = 7 - 16km, which corresponds to a variety of "realistic" equations of state. Measured values of interstellar

SNR	Distance (Kpc)	Diameter (pc)	Age (years)	Temperature (x 10^6 K)
Cas A	2.8	2	300	1.5 - 1.7
Kepler	8.0	-	375	1.8 - 2.2
Tycho	3.0	6	407	1.2 - 1.5
Crab(*)	1.7- 2	1	925	2.0 - 2.4
SN 1006	1.2	4.4	973	0.65 - 0.8
RCW 86	2.5	-	1794	1.4 - 1.8
RCW 103(*)	$\sim$ 2	-	{ $\sim$1000 2000	1.7 - 2.2
MSH15-52(*)	4.2	10	{ $\sim$1600 2100	?
W 28	2.3	10	3400	1.6 - 2.0
G350.0-18	4.0	35	$\sim$8000	1.8 - 2.2
G32.7-0.2	4.8	35	$\sim$10000	2.0 - 2.4
Vela X(*)	0.4	20-40	$\sim$12000	1.2 - 1.5
3C 58(*)	2.6	10-15	?	2.0 - 2.4
CTB 80(*)	3.0	-	?	1.2 - 1.6

Table 1

Characteristics of compact sources in young SNR's

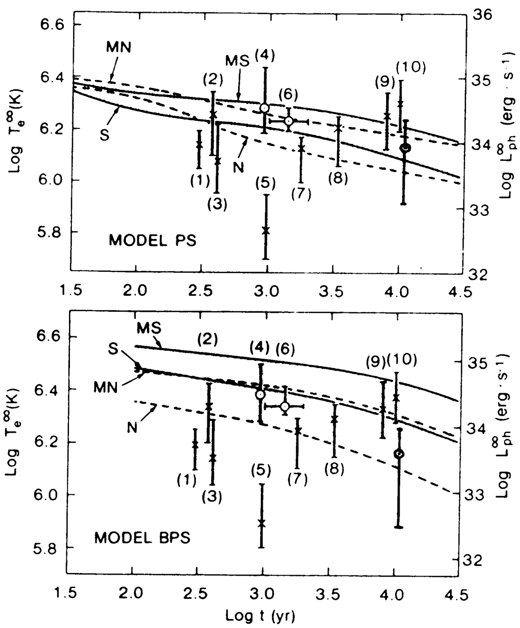

Fig. 3

Comparison between the observational data and the "standard" cooling curves of PS model (top) and BPS model (bottom). T_e^∞ and L_{ph}^∞ are shown as a function of t. The numbers are: (1) Cas A, (2) Kepler, (3) Tycho, (4) Crab, (5) SN1006, (6) RCW103, (7) RCW86, (8) W28, (9) G350.0-18, (10) G22.7-02, and (11) Vela. For BPS model, M = 1.3M☉, ρ^c = 3.2 x 10^{15}gm cm^{-3}, and R = 8.0 km.

density are used whenever known. Otherwise it is assumed to be 0.3 - 1 cm^{-3}. The origin of the point source emission remains unclear. However, it is already interesting in the sense that they strongly suggest the existence of an active neutron star in these remnants.

Our results are compared with the data from the Einstein Observatory in Figure 3, for typical stars of M_G = 1.3M☉. The crosses indicate the observed upper limits to the surface temperature of various SNR's, assuming the presence of neutron stars in these remnants. The circles refer to possible "detections" of point sources. These are accompanied by the estimated error bars which are mostly due to uncertainties in interstellar absorption.

CONCLUSION

Major points of interest are summarised below:

(a) - Some of the observed upper limits (Cas A, SN 1006, Tycho) are below the "standard" theoretical curves (with no drastically fast cooling agents), while they are above the "non-standard" cooling curves with charged pion condensates and quarks. A natural interpretation is that there are no neutron stars in these SNR's, or that these stars contain a substantial amount of such exotic particles as charged pion condensates or quarks.

(b) - If some of the "detections" (e.g. RCW 103, Vela) indeed refer to the surface emission, these "detection" points are consistent with "standard" cooling, while they are inconsistent with charged pion and quark cooling.

(c) - The effect of general relativity on thermal properties such as energy transport and energy balance is negligible.

(d) - The effect of equations of state on observable temperatures is relatively small, and the use of a better equation of state should not change our conclusion (a) and (b).

(e) - The above points confirm our major conclusion reached earlier (Tsuruta 1980, 1981).

(f) - The effect of the finite time scale of thermal conduction is evident for PS model, for a few to several thousand years (see Fig. 1). Many young SNR's are as old as or younger than these ages. That means the isothermal approach is not valid for a stiff model such as PS model. On the other hand, it is adequate for a soft model such as BPS model.

(g) - The use of κ_c(YU) instead of κ_c(FI) should not change our conclusion, because the difference is negligibly small (Fig. 2). Ichimaru et. al. (1982) recently obtained conductive opacity by treating the problem more accurately than Yakovlev-Urpin (YU) and Flowers and Itoh (FI) did. The use of their better opacity, however, should not change our conclusion, because their values generally lie between those of YU and FI.
(h) - If the surface is composed of elements lighter than iron (possible for very young stars), the surface temperature will be higher (at a given age). This is because the conductive opacity will then be decreased (e.g. by a factor of ∿20 for Helium in the critical liquid region). This will further enhance the trend noted in (a). This may be the case e.g. in Cas A.
(i) - The state of the surface matter (gas, solid,etc.) may turn out to be important, and we are currently investigating its effect on cooling.
(j) - If neutral pions are present (a realistic possibility), the surface temperature will be higher again (Tamagaki 1981, Takatsuka 1981), and the trend noted in (a) will be enhanced further.
(k) - The use of better theory of magnetic properties will not change our conclusion (a), because the lower boundary to theoretical temperatures will be determined by a zero-field curve. However, the upper boundary will be determined by a strong field curve. Therefore, the effect of a more "realistic" treatment of magnetic properties should be important if "detections" of the surface temperatures be confirmed.

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REFERENCES

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.
Huebner, W.F., et. al.: 1977. Astrophysical Opacity Library (Rep. No. LA 6760M, Los Alamos Scientific Laboratory).
Ichimaru, S., Itoh, N., Iyetomi, H., and Mitake, S.: 1982. in preparation.
Nomoto, K., and Tsuruta, S.: 1981. Ap. J. Letters 250, p. L19.
Nomoto, K., and Tsuruta, S.: 1982. in preparation.
Pandharipande, V.R., and Smith, R.A.: 1975. Nucl. Phys. A237, p. 507.
Takatsuka, T.: 1981. Proceedings of the 2nd International Conference on "Recent Progress in Many Body Theories", Oaxtepec, Morelos, Mexico.
Tamagaki, R.: 1981. Proceedings of the 2nd International Conference on "Recent Progress in Many Body Theories", Oaxtepec, Morelos, Mexico.
Thorne, K.S.: 1977. Ap. J. 212, p. 825.
Tsuruta, S.: 1980. X-Ray Astronomy (ed. R. Giacconi and G. Setti, Dordrecht: Reidel), p. 73.
Tsuruta, S.: 1981. Pulsars (ed. W. Sieber and R. Wielebinski, Dordrecht: Reidel), p. 331.
Yakovlev, D.G., and Urpin, V.A.: 1980. Sov. Astron. 24, p. 303.