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# Cosmic rays, neutron stars and pulsars

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**Abstract.** The cooling behaviour of neutron stars, taking into account several models proposed by Tsuruta and Cameron, has been studied on the basis of neutrino emission according to the photon–neutrino weak coupling theory. It is shown that the internal energy storage is sufficient to interpret x ray emission and other cosmic ray activities of neutron stars. Also it is found that only one supernova outburst in 100 years can explain the steady state cosmic ray flux in the galaxy. Finally, some remarks about the possible pulsation of neutron stars are made.

## 1. Introduction

The theoretical possibility of the formation of neutron stars was first proposed by Landau (1932). Baade and Zwicky (1934) suggested that neutron stars might be formed during a supernova outburst. The equations of state of neutron matter has been considered by Salpeter (1960) and Levinger and Simmons (1961) and their effects on neutron star structures by Tsuruta and Cameron (1966). Recent observation of x rays from the Crab nebula as well as the exploration of pulsars in supernova remnants has stressed the importance of neutron star theory.

In what way is the rate of energy released after the supernova outburst? This is a very important question if we consider that the supernova remnant is the origin of all the cosmic ray sources within the galaxy (x rays, $\gamma$ rays, etc.). Also this knowledge is essential to have a proper interpretation of pulsars. Various studies of the Crab nebula have shown that it is exceedingly difficult to understand its evolution and the emission of high-energy particles on the assumption that all the energy was injected at the time of the outburst of the supernova about a thousand years ago. Evidence of continuous activity is provided by the moving wisps and by the fact that some parts of the high-energy electrons responsible for radio and optical synchrotron radiation have lifetimes which are short compared with the time which has elapsed since the explosion. If all the energy released in the supernova explosion is emitted during the outburst and all the high-energy particles generated in this way, the continuous activity of the Crab nebula cannot be explained.

The cooling behaviour of neutron stars depends mainly on neutrino emission. The difficulties regarding the cooling behaviour of neutron stars on the basis of neutrino emission according to the current–current coupling theory have been discussed in earlier papers (Bandyopadhyay and Raychaudhuri 1970a,b, Raychaudhuri 1970a). Recently Bandyopadhyay (1968) has proposed that photons can interact weakly with neutrinos and has discussed the astrophysical implications of this photon–neutrino coupling theory of weak processes. The main reasoning behind the argument that photons can interact weakly with neutrinos is as follows. It has been suggested that in view of the neutrino theory of light, photons are likely to interact weakly also, apart from the usual electromagnetic interactions (Bandyopadhyay 1965). Again, it has been argued that photons can interact weakly only with two-component neutrinos and with no other particles, charged or uncharged. Indeed, the coupling constant $g$ for the weak interaction of photons cannot behave as a conserved 'weak charge', since that would require the invariance of the total Lagrangian under the space–time dependent gauge transformations:

$$\psi(x) \rightarrow \exp(-\mathrm{i}g\Lambda)\psi(x)$$
$$A_{\mu}(x) \rightarrow A_{\mu}(x) + \frac{\partial \Lambda}{\partial x_{\mu}}.$$

Also, a gauge-noninvariant interaction is not allowed, as that would permit non-vanishing rest mass of the photon. Thus the weak interaction of photons is possible only in the special case where the gauge transformation of the first kind is not an allowed transformation at all. This condition is satisfied only by a Majorana spinor $\chi$, by virtue of its unique property $\chi = c^{-1}\bar{\chi}$. Now we know that a two-component neutral spinor is equivalent to a four-component Majorana spinor and so photons can interact weakly only with neutrinos. Again Bandyopadhyay *et al.* (1969) have considered the proton–neutrino elastic scattering on the basis of this photon–neutrino coupling theory and have shown that the cross section for the process $\nu + \mathrm{p} \rightarrow \nu + \mathrm{p}$ is at least an order smaller than that of the process $\bar{\nu} + \mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^{+}$, which is well within the experimental upper limit. Also from an analysis of the synchroton radiation of neutrinos (Raychaudhuri 1970b) and plasma neutrino process (Raychaudhuri 1970c), it is possible to interpret the fact that only a small fraction ($\sim$ 10%) of the observed white dwarfs have masses greater than $0{\cdot}9\, M_{\odot}$. Raychaudhuri (1970a) has shown that the x rays coming from a neutron star along the direction of the Crab nebula can be interpreted as the thermal emission of the star when the cooling behaviour is examined according to the photon–neutrino coupling theory of the neutrino emission processes. In this paper we investigate the cooling behaviour of neutron stars of several models according to the photon–neutrino coupling theory, and determine their direct consequences.

## 2. Neutrino luminosity and cooling behaviour of a neutron star

A neutron star is formed probably through the free fall collapse of a supernova. This means that such a star does not arrive easily at its stable configuration. Large dynamical velocities are developed during the infall of a remnant and a stable configuration cannot be formed until the dynamical oscillations that occur about the stable configuration have been damped away. The associated energies are very large, since the dynamical speeds are not much less than that of light, say $C/3$ (for the situation in which the dimensions of the equilibrium structure are not much greater than the critical Schwarzschild radius), giving of the order of $10^{20}$ erg g$^{-1}$. The total energy for a remnant of mass $1\, M_{\odot}$ is approximately $2 \times 10^{53}$ erg for example.

Since a neutron star is a remnant core of a supernova explosion, its surface composition is likely to be that of equilibrium composition, e.g. Fe. Within seconds of its formation a neutron star is likely to possess an interior temperature of $10^{12}$ K, which is the maximum temperature achieved in collapse (Chiu 1964).

So far as the cooling behaviour is concerned we have mentioned in an earlier paper (Bandyopadhyay and Raychaudhuri 1970a,b, Raychaudhuri 1970a) that the existence of the process $\mathrm{n} + \mathrm{n} \rightarrow \mathrm{n} + \mathrm{p} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$ is questionable and as such we neglect it here. Chiu and Salpeter (1964) pointed out that the plasma neutrino emission rate when calculated according to the current–current coupling theory is a maximum near $4T_9{}^3\, 10^{10}$ g cm$^{-3}$. Therefore for density $10^{15}$ g cm$^{-3}$ the maximum rate of neutrino emission from the plasma neutrino process is at the temperature $T_c \simeq 3\times 10^{10}$ K. We have shown that the NSR (neutrino synchrotron radiation) process alone would lead to an observable effect in a neutron star when the photon–neutrino weak coupling theory is taken into account, and the rate of emission of neutrinos is greater than the plasma neutrino emission process (Raychaudhuri 1970a).

A neutron star typically has densities of the order of $10^{15}$ g cm$^{-3}$ and electron Fermi energy of the order of 100 MeV. Though Landstreet (1965) pointed out the uncertainty in the NSR luminosity calculation by invalidating some very important approximations, yet it can be taken to be valid up to $kT \ll 100$ MeV. For our NSR luminosity calculation we take $kT \simeq 30$ MeV which is less than 100 MeV. Synchrotron radiation of neutrinos ($e^- \rightarrow e^- + \nu_e + \bar{\nu}_e$) gives the neutrino luminosity according to the photon–neutrino coupling theory (Raychaudhuri 1970a)

$$l_\nu \simeq 3\times 10^{-7} H_8^{2/3} T_7^{7/3} n_e^{4/9} \qquad (\mathrm{erg\,cm^{-3}\,s^{-1}}). \tag{1}$$

Here $H_8 = H/10^8$ being the magnetic field strength and $T_7 = T/10^7$, $T$ being the temperature in K. Woltjer (1964) has suggested the possible existence of magnetic field as high as $10^{14}$ G.

The total neutrino luminosity is calculated from the relation (Landstreet 1965).

$$L_\nu = \int_0^R 4\pi r^2 l_\nu(n_e, T_c, H)\,\mathrm{d}p \qquad (\mathrm{erg\,s^{-1}}). \tag{2}$$

The cooling time $\tau$ can be computed from the relation

$$\tau = \frac{U_T}{L_{\mathrm{ph}} + L_\nu} \tag{3}$$

where $U_T$ is the total energy content of the star at temperature $T$. $L_{\mathrm{ph}}$ and $L_\nu$ are the photon and neutrino luminosity respectively.

The thermal energy $U_T$ is given by the relation

$$U_T = \frac{3}{2}\pi^2\left(\frac{kT_c}{m_n c^2}\right)^2 c^2 \int_0^R \frac{1}{x^2}\left(\frac{3}{4}+x\right)4\pi r^2 \rho\,\mathrm{d}r \tag{4}$$

where $x$ is the degeneracy parameter, defined by

$$\rho = \frac{8\pi}{3}\frac{m_n^3 c^3}{h^3} m_n x^3. \tag{5}$$

An estimate gives

$$U_T = 10^{29\cdot 44} T_c^2. \tag{6}$$

The neutrino luminosity (NSR) according to the photon–neutrino coupling theory together with photon luminosity and the total energy content of the neutron star are tabulated in tables 1, 2 and 3 (as calculated by Tsuruta and Cameron 1966 for Fe atmosphere) for the models of neutron star ranges from $0{\cdot}2\,M_\odot$ to $1\,M_\odot$ and for the ranges of temperature $T_e \simeq 10^9$ K to $T_e \simeq 10^4$ K.

**Table 1. The characteristics of the hot neutron star model ($V_\beta$, $1M_\odot$) with Fe atmosphere**

| $T_e$(K) | lg $L_{ph}$ (erg $s^{-1}$) | lg $L_\nu$ (erg $s^{-1}$) | lg $T_c$(K) | lg $U_T$ (erg) | lg $\tau$ (years) |
|---|---|---|---|---|---|
| $10^9$ | 44·28 | 42·11 | 11·32 | 52·08 | 0·30 |
| $5\times10^8$ | 43·08 | 41·41 | 11·02 | 51·58 | 0·89 |
| $2\times10^8$ | 41·49 | 40·52 | 10·64 | 50·72 | 1·69 |
| $10^8$ | 40·28 | 39·80 | 10·33 | 50·10 | 2·20 |
| $5\times10^7$ | 39·08 | 39·08 | 10·02 | 49·48 | 2·60 |
| $2\times10^7$ | 37·49 | 37·69 | 9·44 | 48·32 | 2·92 |
| $10^7$ | 36·28 | 36·65 | 9·03 | 47·51 | 3·21 |
| $5\times10^6$ | 35·08 | 35·88 | 8·70 | 46·84 | 3·40 |
| $2\times10^6$ | 33·49 | 34·71 | 8·22 | 45·84 | 3·60 |
| $10^6$ | 32·28 | 33·59 | 7·74 | 44·88 | 3·77 |
| $5\times10^5$ | 31·08 | 32·54 | 7·29 | 44·01 | 3·95 |
| $2\times10^5$ | 29·49 | 30·98 | 6·62 | 43·71 | 4·22 |
| $10^5$ | 28·28 | 29·95 | 6·18 | 41·78 | 4·32 |
| $5\times10^4$ | 27·08 | 28·83 | 5·70 | 40·86 | 4·52 |
| $2\times10^4$ | 25·49 | 27·36 | 5·07 | 39·61 | 4·74 |

$T_e$ and $T_c$ are the surface and core temperatures, $L_{ph}$ is the photon luminosity, $L_\nu$ is the neutrino luminosity (NSR) according to the photon neutrino coupling theory, $U_T$ is the internal energy and $\tau$ is the cooling time.

**Table 2. The characteristics of the hot neutron star model ($V_\beta$, 0·6 $M_\odot$) with Fe atmosphere**

| $T_e$(K) | lg $L_{ph}$ (erg $s^{-1}$) | lg $L_\nu$ (erg $s^{-1}$) | lg $T_c$(K) | lg $U_T$ (erg) | lg $\tau$ (years) |
|---|---|---|---|---|---|
| $10^9$ | 44·56 | 42·21 | 11·40 | 52·24 | 0·18 |
| $5\times10^8$ | 43·36 | 41·50 | 11·10 | 51·64 | 0·77 |
| $2\times10^8$ | 41·77 | 40·58 | 10·70 | 50·84 | 1·54 |
| $10^8$ | 40·56 | 39·88 | 10·40 | 50·24 | 2·10 |
| $5\times10^7$ | 39·36 | 39·13 | 10·08 | 49·60 | 2·54 |
| $2\times10^7$ | 37·77 | 38·20 | 9·68 | 48·74 | 2·90 |
| $10^7$ | 36·56 | 37·23 | 9·26 | 47·88 | 3·07 |
| $5\times10^6$ | 35·36 | 36·37 | 8·90 | 47·17 | 3·26 |
| $2\times10^6$ | 33·77 | 35·42 | 8·47 | 46·30 | 3·37 |
| $10^6$ | 32·56 | 34·42 | 8·04 | 45·51 | 3·58 |
| $5\times10^5$ | 31·36 | 33·32 | 7·57 | 44·60 | 3·78 |
| $2\times10^5$ | 29·77 | 31·78 | 6·91 | 43·26 | 3·98 |
| $10^5$ | 28·56 | 30·68 | 6·44 | 42·30 | 4·12 |
| $5\times10^4$ | 27·36 | 29·61 | 5·98 | 41·35 | 4·24 |
| $2\times10^4$ | 25·77 | 28·16 | 5·36 | 40·10 | 4·44 |
| $10^4$ | 24·36 | 26·90 | 4·82 | 39·03 | 4·63 |

$T_e$ and $T_c$ are the surface and core temperatures, $L_{ph}$ is the photon luminosity, $L_\nu$ is the neutrino luminosity (NSR) according to the photon–neutrino coupling theory, $U_T$ is the internal energy and $\tau$ is the cooling time.

**Table 3. The characteristics of the hot neutron star model ($V_\beta$, 0·2 $M_\odot$) with Fe atmosphere**

| $T_e$(K) | lg $L_{ph}$ (erg s$^{-1}$) | lg $L_\nu$ (erg s$^{-1}$) | lg $T_c$(K) | lg $U_T$ (erg) | lg $\tau$ (years) |
|---|---|---|---|---|---|
| $5\times10^8$ | 44·17 | 42·08 | 11·35 | 52·14 | 0·47 |
| $2\times10^8$ | 42·58 | 41·26 | 11·00 | 51·44 | 1·34 |
| $10^8$ | 41·37 | 40·68 | 10·75 | 50·94 | 1·99 |
| $5\times10^7$ | 40·17 | 40·07 | 10·49 | 50·42 | 2·50 |
| $2\times10^7$ | 38·58 | 39·25 | 10·14 | 49·72 | 2·87 |
| $10^7$ | 37·37 | 38·34 | 9·75 | 48·91 | 3·03 |
| $5\times10^6$ | 36·17 | 37·31 | 9·33 | 48·21 | 3·28 |
| $2\times10^6$ | 34·58 | 36·16 | 8·84 | 47·12 | 3·45 |
| $10^6$ | 33·37 | 35·38 | 8·52 | 46·50 | 3·62 |
| $5\times10^5$ | 32·17 | 34·42 | 8·11 | 45·68 | 3·76 |
| $2\times10^5$ | 30·58 | 32·97 | 7·49 | 44·40 | 3·93 |
| $10^5$ | 29·37 | 31·83 | 7·00 | 43·44 | 4·11 |
| $5\times10^4$ | 28·17 | 30·69 | 6·51 | 43·50 | 4·31 |
| $2\times10^4$ | 26·58 | 29·29 | 5·91 | 41·26 | 4·47 |
| $10^4$ | 25·37 | 28·17 | 5·43 | 40·31 | 4·64 |

$T_e$ and $T_c$ are the surface and core temperature, $L_{ph}$ is the photon luminosity, $L_\nu$ is the neutrino luminosity (NSR) according to the photon–neutrino coupling theory, $U_T$ is the internal energy and $\tau$ is the cooling time.

We see from the tables 1, 2 and 3 that all models of neutron stars with $T_e \simeq 10^7$ K cool slowly for observation, while the strong absorption of x rays from a neutron star by interstellar gas makes it very difficult for us to observe a neutron star with $T_e < 10^6$ K. The stellar luminosity is low at $T_e \simeq 10^6$ K. Hence the most important range of temperature of neutron stars from the point of view of observation is $T_e > 10^6$ K. A neutron star will be $10^3$ years old when $T_e \simeq 10^7$ K for the surface composition of Fe, and it will take approximately $4\times10^3$ years before it cools down to $T_e \simeq 10^6$ K.

## 3. Observation problem and discussion

It was mentioned in § 2 that the stable configuration of a neutron star cannot be achieved until the dynamical oscillations that occur about the stable configuration have been damped away. After the supernova outburst the total energy of a remnant of mass 1 $M_\odot$ is approximately $2\times10^{53}$ erg. A large flux of relativistic electrons is currently present in many supernova remnants and it is expected that this in part is the remnant of a much larger flux of relativistic particles (i.e. protons) which was produced probably in the early stages of the outburst. If the larger flux of relativistic particles is originally confined in an expanding shell containing a magnetic field then, because of the high density in the shell, they will largely be destroyed in a few days and their energy will be dissipated in the form of neutrinos, $\gamma$-rays, electrons and positrons which radiate in the magnetic field. Burbidge (1966) expected that a large flux of ($\geqslant$ 50 MeV) $\gamma$ rays will thus be generated at a rate of $10^{44}$ to $10^{45}$ erg$^{-1}$ during this period. The energy requirement for the generation of $\gamma$ rays ($\geqslant$ 50 meV) at the rate of $10^{44}$ erg s$^{-1}$ is met by a neutron star within 1 to 3 years of its formation as is evident from the tables. So the remnants of a supernova can dissipate their energy in the early state by the generation of larger flux of relativistic particles (e.g. protons), neutrinos, $\gamma$ rays, electrons and positrons. However, when the core temperature of the neutron star falls below $10^{10}$ K, the energy of the star is dissipated mainly by the neutrino synchrotron radiation process.

The primary cosmic ray flux in our own galaxy is probably made up of several components (Morrison 1961). Ginzburg and Syrovatsky (1961) have argued that the contribution comes from peculiar stars of various types, as manifested by peculiar abundances and other evidence of surface nuclear activity, must be rather small. They have concluded that the supernova makes the major contribution to the primary cosmic ray flux. Synchrotron radiation emitted by supernova remnants indicates that high-energy particles are actually present, that acceleration is still going on centuries after the explosive stage. The particles that radiate are electrons of energy $10^9$ to $10^{10}$ eV but presumably there are also energetic protons and other nuclei.

Cosmic $\gamma$ rays are expected from decay of neutral pions produced by nuclei and from collisions of electrons with photons by the inverse Compton effect. For a reasonable magnitude of the magnetic field, the synchrotron radiation may not lie in the x ray or $\gamma$ ray range. It is expected that the cosmic $\gamma$ rays may be anisotropic. Various efforts have been made to detect anisotropic $\gamma$ rays. Recently Frye *et al.* (1969) found evidence for a point source of high-energy cosmic $\gamma$ rays (above 50 MeV) in the region of Sagittarius. As mentioned earlier our cooling rate suggests that these $\gamma$ rays come from a nascent neutron star from a supernova outburst. Ginzburg and Burbidge pointed out that if a larger flux of relativistic protons was generated in the source it would be dissipated only by escape from the system or by collisions with the ambient gas in the system. In collisons the flux could be converted via meson decays to electrons, positrons, $\gamma$ rays and neutrinos. It is thus possible that the electron–positron flux responsible for the synchrotron emission is largely a secondary flux, and a proton flux continuously rejuvenates the radiating particles.

Again from the tables 1, 2 and 3 we see that after 100 years the neutron star radiates energy ($10^{40}$ to $10^{41}$) erg $s^{-1}$. This is significant in the sense that if we take the supernova as the main source of all cosmic rays in the galaxy then, to maintain the steady-state cosmic ray intensity, the galaxy needs an input of energy ($10^{40}$ to $10^{41}$) erg $s^{-1}$ from supernova remnants. The galactic supernova occurs at the rate $10^{-2}$/year, so only one supernova remnant is sufficient to maintain the steady cosmic ray intensity in the galaxy from our result.

The nature of a supernova remnant is complex; the observed x rays can be due to nonthermal radiation from the hot gas clouds, the thermal radiation from the neutron star or a mixture of both. The question of whether the thermal component is greater than the nonthermal component, in the case where both are present, can be decided if the relative strength of each component is known. If a neutron star emits x ray radiation as a black body, the wave length $\lambda_{max}$ giving the maximum intensity in the spectrum is given by

$$\lambda_{max} = \frac{hc}{4{\cdot}97kT_e} \simeq \frac{0{\cdot}29}{T_e} \tag{7}$$

where $\lambda$ is in cm and $T_e$ in $k$.

This simple relation indicates that when $T_e \sim 10^6$ to $10^9$ K, the maximum comes in the x ray region 30 Å $> \lambda_{max} >$ 0·03 Å. A neutron star takes 1 year to $4\times10^3$ years before it cools down to $T_e \sim 10^6$ K, depending on the model of the star, i.e. a neutron star can last sufficiently long enough to allow our observation in the x ray region. We know from observation (Burbidge 1966) that the flux of (10 to 50) keV x rays is not explicable in terms of thermal source, since a surface temperature of the order of $10^8$ K is required and at that temperature the neutron star will remain (100 to 150) years depending on the model of neutron star when neutrino loss is calculated according to the photon–neutrino coupling theory. Now we consider the problem of x ray fluxes from the Scorpius and Crab source. If we know the distance $d$, and the photon luminosity $L$ of a neutron star, the flux $F$ of the thermal component of x rays reaching the region just above our atmosphere is found from

$$F = \frac{L}{4\pi d^2} \qquad (\mathrm{erg\,s^{-1}\,cm^{-2}}). \tag{8}$$

For Scorpius XR-I, taking the surface temperatures of 1 or $2\times10^6$ K consistent with the soft x ray fluxes measured by the Friedman group, the photon luminosity of the star can also be predicted (Tsuruta and Cameron 1966).

If the x ray source in Sco XR-I is indeed the remnant of a supernova about 170 parsec away and about $10^6$ years old, from table 4 we see that all models of neutron stars can be excluded as the sources of thermal x rays because they are too young. Sandage *et al.* (1966) reported that the source Sco XR-I appears to be identified with a faint, blue nova-like object. Again from table 5 we see that the x ray source in the Crab nebula (Tau XR-I) gives rise to x ray flux of approximately $10^{-7}$ erg cm$^{-2}$ s$^{-1}$ at a surface temperature of the order of $10^7$ K. So the x ray source in the Crab nebula can be interpreted as the thermal emission of x rays from a neutron star, for an x ray wavelength $\lambda \simeq 3$ Å, absorption by interstellar gas is small even across the whole galactic disk. Friedman (1968) has pointed out that the observational evidence is still so incomplete and often so marginal that serious arguments can be made for thermal x ray processes in the Crab. Indeed, roughly about 10% of the total x ray intensity from the Crab is apparently from the pulsar (i.e. the neutron star in the core), as it comes in pulses.

We now consider the pulsar phenomena which is the most perplexing astrophysical problem in recent years. Considering the synchrotron radiation of neutrinos as the dissipation mechanism for neutron stars, Bandyopadhyay and Raychaudhuri (1970a) have proposed that a pulsar may be a radially pulsating magnetic neutron star. We have shown that the rate of change of period $\Delta p/p \simeq \mathrm{d}p/\mathrm{d}t$, is given by

$$-\frac{\Delta p}{p} = \frac{1}{2}\frac{p}{E_T}\frac{\mathrm{d}E_T}{\mathrm{d}t}. \tag{9}$$

Also, the model suggests that the frequency of pulsation is related to the temperature by the following relation

$$\omega \simeq \frac{9{\cdot}5}{10^8}T_c. \tag{10}$$

Observationally, we know that in the case of the Crab pulsar $\mathrm{d}p/\mathrm{d}t$ is $10^{-12}$. The rate of neutrino energy loss for the Crab pulsar is found to be $10^{38}$ erg s$^{-1}$ which is of the right order of magnitude to interpret the increase in period with time. The rate of change of $\Delta p/p \simeq \mathrm{d}p/\mathrm{d}t$ has been measured in the case of the Crab pulsar NP 0532 and the measured value is $-2\times10^{-24}$ (Chiu 1969). This can be accounted in our case as we find

$$\frac{\mathrm{d}^2p}{\mathrm{d}t^2} \simeq -8\times10^{-24}. \tag{11}$$

At present, the observed pulse period of various pulsars is known to range from

**Table 4. The observational problem of Sco XR-I ($T_e$ is the surface temperature, $\tau$ the age of the neutron star, Flux is the thermal component of x rays from a neutron star)**

| For Fe atmosphere | ($V_\beta$, 0·2 $M_\odot$) | | ($V_\beta$, 0·6 $M_\odot$) | | ($V_\beta$, 1·0 $M_\odot$) | |
|---|---|---|---|---|---|---|
| | $T_e = 2 \times 10^6$(K) | $T_e = 1 \times 10^6$(K) | $T_e = 2 \times 10^6$(K) | $T_e = 1 \times 10^6$(K) | $T_e = 2 \times 10^6$(K) | $T_e = 1 \times 10^6$(K) |
| lg $L_{ph}$ (erg $s^{-1}$ | 34·58 | 33·37 | 33·77 | 32·56 | 33·49 | 32·28 |
| Flux (erg $cm^2$ $s^{-1}$) | $1{\cdot}12 \times 10^{-8}$ | $6{\cdot}92 \times 10^{-10}$ | $1{\cdot}74 \times 10^{-9}$ | $1{\cdot}07 \times 10^{-10}$ | $9{\cdot}12 \times 10^{-10}$ | $5{\cdot}62 \times 10^{-11}$ |
| lg $\tau$ (years) | 3·45 | 3·62 | 3·37 | 3·58 | 3·60 | 3·77 |

$d$ = 170 parsec to be observed above the earth's atmosphere (Tsuruta and Cameron 1966). $L_{ph}$ = photon luminosity of the star.

**Table 5. The observational problem of Tau XR-I**

| For Fe atmosphere | ($V_\beta$, 0·2 $M_\odot$) | ($V_\beta$, 0·6 $M_\odot$) | ($V_\beta$, 1·0 $M_\odot$) |
|---|---|---|---|
| lg $T_e$(K) | 7·12 | 7·20 | 7·23 |
| $L_{ph}$ (erg s$^{-1}$) | 7·4 $\times 10^{37}$ | 2·19 $\times 10^{37}$ | 1·58 $\times 10^{37}$ |
| Flux (erg cm$^2$ s$^{-1}$) | 4·55 $\times 10^{-7}$ | 1·34 $\times 10^{-7}$ | 9·73 $\times 10^{-8}$ |

0·03 s to 3·7 s. From table 2 and from the temperature and frequency relation equation (10) we may expect from the observed range of pulsar period that there may be 100 pulsars in our galaxy. At present almost 50 pulsars have been found (*Nature News* 1970).

From our above discussions we conclude that the cooling behaviour of neutron stars when calculated according to the photon–neutrino coupling theory of neutrino emission processes suggests that the internal energy of a neutron star is sufficient to interpret the cosmic ray activities, generation of x rays and the pulsation phenomenon from supernova remnants.

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