NEUTRON STARS AS X-RAY SOURCES

DONALD C. MORTON
Princeton University Observatory
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ABSTRACT

Neutron stars are considered as the origin of the X-ray emission from Scorpius and the Crab Nebula. For a sequence of interior temperatures from 2×10^{9} ° to 2×10^{7} ° K, a simple, analytic model atmosphere is fitted to a typical degenerate neutron core with mass 1 3 $M_{\odot}$ and radius 9.25 km. Opacity from either electron scattering or bound-free absorption reduces the effective surface temperature to 1.6×10^{7} ° to 7 7 $\times 10^{5}$ ° K. Except for the coolest models, the predicted X-ray luminosities are high enough to explain the observed Scorpius flux with a neutron star 1200 to 100 pc distant.

Thermal calculations show that a neutron star at these distances can remain a detectable source for a few thousand years at most. The data for the Crab Nebula indicate that it began its thermal history with a core temperature of 5.0×10^{8} ° K and that it has now cooled to 2.3×10^{8} ° K with an effective temperature of 7 6 $\times 10^{6}$ ° K.

During the past two thousand years Chinese, Japanese, and Arab astronomers have recorded five new stars in the vicinity of the Scorpius source. One of these might have been a supernova and have left a neutron star remnant.

I. INTRODUCTION

During a rocket flight on April 29, 1963, Bowyer, Byram, Chubb, and Friedman (1963) detected two discrete X-ray sources in the night sky, one north of ν Scorpii and the other coincident with the Crab Nebula. A honeycomb collimator in front of the detector established the positions of the sources within 2° and their diameters as less than 5°. The Scorpius source must be the one reported near the galactic center by Giaconni, Gursky, Paolini, and Rossi (1962, 1963), but the wide fields of their detectors prevented any accurate estimates of the position and diameter of the source.

Friedman located the stronger X-ray object in Scorpius at $\alpha = 16^{h}15^{m}$, $\delta = -15°$ in a region thickly populated with stars but devoid of all but the faintest wisps of nebulosity on the *Palomar Sky Atlas*. No radio source is known in this part of the sky. The galactic latitude is $+23°$. The Crab Nebula, however, is a well-known source of visible and radio synchrotron emission. The observed fluxes were 1.4×10^{-8} erg sec^{-1} cm^{-2} A^{-1} for Scorpius and 2×10^{-9} erg sec^{-1} cm^{-2} A^{-1} for the Crab, over the 1.5–8-Å band width of the detector with an effective wavelength of 5 Å. Comparison of the counts in two parts of this interval showed that the spectrum was approximately flat in frequency units.

To explain the Scorpius emission it is necessary to postulate an object which radiates X-rays strongly but no significant visual or radio energy. Chiu (1964) has suggested such an object—a neutron star with a surface temperature about 10^{7} ° K radiating as a black body.

The neutron star is an end state of stellar evolution similar to the white dwarf, except that the central density at some time has become greater than 3.4×10^{11} gm cm^{-3} (Hamada and Salpeter 1961), causing the nuclei to capture electrons and become neutrons which are in a degenerate state. It is expected that the neutrons are only partially degenerate with a finite temperature, having some thermal energy available for the star to radiate.

Early calculations by Oppenheimer and Volkoff (1939) and more recent ones by Harrison, Wakano, and Wheeler (1958) have indicated mass limits of about 1 $\odot$ and radii of some 10 km for neutron stars. Consequently the central densities and surface gravities must be extremely high. Cameron (1959) has constructed a series of models over a wide range of central densities with an equation of state based on a simple three-body effective nuclear potential for a non-relativistic neutron gas. He found an observable mass limit of

2.01 $M_\odot$ corresponding to 3.00 $M_\odot$ contracting from infinity. Saakyan (1963) has applied a correction to Cameron's equation of state, reducing the observable mass limit to 1.7 $M_\odot$, still greater than the white-dwarf limit. For the calculations of this paper we shall assume that a typical neutron star is represented by the following mass, radius, central density, mean density, and surface gravity, all consistent with Cameron's models:

$$M = 1.3\ M_\odot = 2.6 \times 10^{33}\ \text{gm}, \qquad R = 9.25\ \text{km},$$

$$\rho_c = 1.46 \times 10^{15}\ \text{gm cm}^{-3}, \quad \langle\rho\rangle = 7.85 \times 10^{14}\ \text{gm cm}^{-3}, \quad g = 2.0 \times 10^{14}\ \text{cm sec}^{-2}.$$

Saakyan's correction is significant only at higher masses. For a wide range of central densities, including the one above, Cameron (1959) has shown that the density is constant throughout more than half the volume of the core.

The neutron star may originate from a collapsing stellar core that triggers a supernova explosion. The imploding shock wave started by the collapse could compress the core to nuclear density at a high temperature. If this temperature is much greater than 10^9 ° K, Chiu (1964) has indicated that neutrino processes would rapidly dissipate the energy before the core had time to rebound, leaving a neutron star. An alternative origin could be from a red giant with exhausted nuclear energy sources whose mass exceeds the white-dwarf limit of 1.4 $M_\odot$ but not the neutron-star limit of 1.7 $M_\odot$. Such a star would contract slowly until the central temperature is high enough for the neutrino processes to dominate in radiating away the gravitational energy. Then it rapidly would approach the equilibrium configuration of a neutron star. Of course, this second scheme is irrelevant if more accurate models of a neutron star show that its mass limit is less than that for a white dwarf. Hamada and Salpeter (1961) have indicated that the white-dwarf mass limit may be as low as 1.01 $M_\odot$ if the effects of the density on composition are considered. However, one series of neutron-star models by Ambartsumian and Saakyan (1962), including strange particles, has a mass limit 1.028 $M_\odot$.

The following calculations form a first approximation to determine the surface temperature, X-ray emission, and cooling time of a neutron star. The results are more relevant to the supernova hypothesis of origin, since neither hydrogen nor helium is included to the models. According to Hamada and Salpeter (1961), the neutron core is surrounded by a layer of ordinary ionized nuclei and degenerate electrons at white-dwarf densities, which is relatively thin for densities of 6×10^{14} or greater. Consequently a non-degenerate atmosphere of electrons and heavy nuclei is fitted to a region of non-relativistic degenerate electrons and non-degenerate heavy nuclei. The procedure is similar to that used by Schwarzschild (1958) to construct a white-dwarf atmosphere; his notation is followed here with a few exceptions. The fitting of the layer of degenerate electrons to the neutron core is not considered, since the high efficiency of conduction by degenerate particles leaves the whole core at essentially the same temperature.

II. OPACITY RELATIONS AND GAS LAWS

The Rosseland mean opacity is assumed to be either electron scattering with a coefficient

$$\sigma_e = 0.19\ \text{cm}^2\ \text{gm}^{-1}, \tag{1}$$

or bound-free absorption represented by a modification of Kramers' formula,

$$\kappa = \kappa_0 \rho^{1-\alpha} T^{-7/2} = 1.4 \times 10^{25} \rho^{1/2} T^{-7/2}\ \text{cm}^2\ \text{gm}^{-1}. \tag{2}$$

The coefficient and the exponent of ρ are obtained by fitting to the tables of Keller and Meyerott (1955) for Mixture XII consisting entirely of heavy elements. Equation (2) matches the tabulated values or their extrapolations within a factor of 3 for $10^{-2} \leq \rho \leq 10^5$. In the neutron star considered here, bound-free absorption always dominates in the outer layers of the atmosphere, but it decreases with depth, and for the hotter models electron scattering is stronger in a layer near the degenerate core. For simplicity in integrating the equations, the opacity is assumed to result from one or the other source, whichever is greater. The outer layer with Kramers' opacity is fitted to an inner shell with electron scattering at a boundary a where the two opacities are equal, as shown in Figure 1.

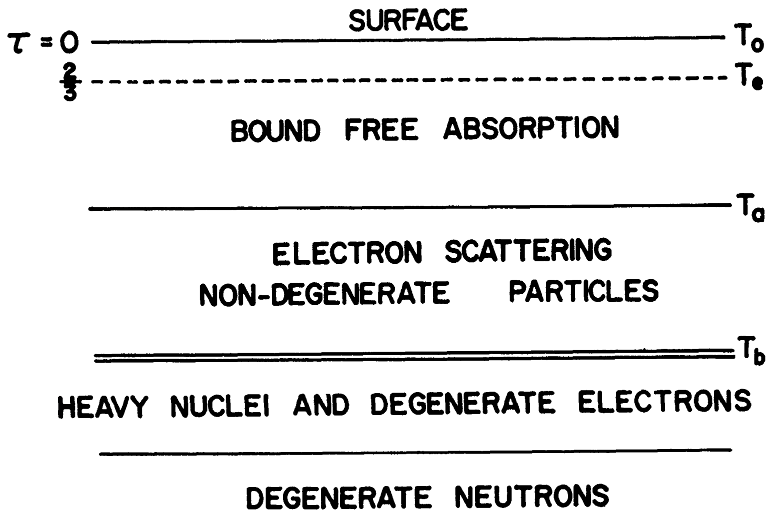

FIG 1.—Schematic representation of the atmosphere of a neutron star

The pressure in the non-degenerate atmosphere is given by the ideal gas law,

$$P = \frac{k}{\mu m_H} \rho T \,, \tag{3}$$

where the mean molecular weight μ is taken as 2 for the heavy elements. The pressure in the outer layer of the core is provided by the non-relativistic degenerate electrons. The atmosphere is fitted to the core at a boundary b where the two electron pressures are equal. There

$$\rho_b = \mu_e \left(\frac{k}{m_H K_1}\right)^{3/2} T_b^{3/2} = 4.80 \times 10^{-8} T_b^{3/2} \text{ gm cm}^{-3} \,, \tag{4}$$

with

$$K_1 = \frac{h^2}{20 m_e m_H} \left(\frac{3}{\pi m_H}\right)^{3/2} = 9.91 \times 10^{12} \,, \tag{5}$$

and μ_e, the mean molecular weight of the electrons, equals 2.

Substitution of this equation for ρ_b in the Kramers' formula (2) gives the bound-free opacity at the core boundary. Equating this to the scattering coefficient gives the limiting core temperature $T_b{}^*$ above which it is necessary to consider an intermediate layer of electron scattering.

$$T_b{}^* = \left[\mu_e \left(\frac{k}{m_H K_1}\right)^{3/2} \frac{\kappa_0{}^2}{\sigma_e{}^2}\right]^{2/11} = 1.19 \times 10^8 \,{}^\circ\mathrm{K} \,. \tag{6}$$

III. ATMOSPHERIC MODELS

For the outer layer of bound-free absorption the Eddington approximation for the solution of the transfer equation and the assumption of local thermodynamic equilibrium have been adopted to give

$$T^4 = T_0{}^4 (1 + \tfrac{3}{2} \tau) = \tfrac{1}{2} T_e{}^4 (1 + \tfrac{3}{2} \tau) \,, \tag{7}$$

where

$$\tau = -\int_0^z \kappa\rho\, dz\,, \tag{8}$$

and T_0 and T_e are the surface and effective temperatures, respectively. The equation of hydrostatic equilibrium assumes the form

$$\frac{dP}{d\tau} = \frac{g}{\kappa}. \tag{9}$$

Combining equations (2), (3), and the derivative of (7) with (9) results in an equation for dP/dT which can be integrated directly. Application of the boundary condition $P = 0$ at $T = T_0$ and substitution again of the ideal gas law finally gives

$$\rho^{3/2} = \frac{1}{2}\frac{\mu m_H}{k}\frac{g}{\kappa_0}\frac{T^{13/2}}{T_0^4}\left[1-\left(\frac{T_0}{T}\right)^8\right] = 1.73\times 10^{-19}\frac{T^{13/2}}{T_0^4}\left[1-\left(\frac{T_0}{T}\right)^8\right]. \tag{10}$$

If $T_b \leq 1.19 \times 10^8$, Kramers' opacity dominates throughout the whole atmosphere and this equation for ρ is fitted to the degenerate electron layer at the boundary b using equation (4). Then

$$\begin{aligned} T_0^4 &= \frac{1}{2}\left(\frac{m_H}{k}\right)^{13/4} K_1^{9/4}\frac{\mu}{\mu_e^{3/2}}\frac{g}{\kappa_0}T_b^{17/4}\left[1-\left(\frac{T_0}{T}\right)^8\right] \\ &= 1.63\times 10^{-8}\, T_b^{17/4}\left[1-\left(\frac{T_0}{T}\right)^8\right]. \end{aligned} \tag{11}$$

The temperature ratio T_0/T_b is always small enough that the term in brackets can be equated to unity. Then $(T_b/T_0)^4$ and hence the optical depth at b are both proportional to $T_b^{-1/4}$ so that they increase with decreasing T_b.

At core temperatures higher than $1.19 \times 10^8\,°$ K, electron scattering dominates in an intermediate layer between the bound-free region and the core. The solution for Kramers' opacity, equation (10), is followed down to the boundary a where

$$\sigma_e = \kappa_0 \rho_a^{1/2} T_a^{-7/2}\,. \tag{12}$$

Consequently,

$$T_a^4 = \frac{1}{2}\frac{\mu m_H}{k}\frac{\kappa_0^2}{\sigma_e^2}\frac{g}{T_0^4}\left[1-\left(\frac{T_0}{T_a}\right)^8\right] = 6.69\times 10^{58}\frac{1}{T_0^4}\left[1-\left(\frac{T_0}{T_a}\right)^8\right]. \tag{13}$$

In the scattering layer below this, the optical depth is

$$\tau = \tau_a - \int_{z_a}^{z}(\sigma_e + \kappa)\rho\, dz \approx \tau_a - \int_{z_a}^{z}\sigma_e \rho\, dz\,. \tag{14}$$

However, in the solution of the transfer equation, the scattering terms cancel when the constant-flux condition is applied so that the remaining small fraction of bound-free absorption must be considered in order to obtain the temperature distribution

$$T^4 = T_a^4 + \tfrac{3}{2}T_0^4(\tau - \tau_a)\,. \tag{15}$$

The hydrostatic equation can be integrated directly with respect to τ for the result that

$$P = P_a + \frac{g}{\sigma_e}(\tau - \tau_a). \tag{16}$$

These equations are combined with the ideal gas law to give

$$\rho T = -\frac{1}{12}\left(\frac{\mu m_H}{k}\right)^2\frac{\kappa_0^2}{\sigma_e^4}\frac{g^2}{T_0^8} + \frac{2}{3}\frac{\mu m_H}{k}\frac{g}{\sigma_e}\frac{T^4}{T_0^4}. \tag{17}$$

Fitting this to the layer of degenerate electrons at the boundary b, determined by equation (4), gives a quadratic equation for T_0^4 as a function of T_b. Consideration of the limiting case with $T_b = 1.19 \times 10^8$ indicates that the positive root must be chosen.

$$T_0^4 = \frac{2}{3}\left(\frac{m_H}{k}\right)^{5/2} K_1^{3/2} \frac{\mu}{\mu_e} \frac{g}{\sigma_e} T_b^{3/2} \frac{1}{2} \left\{1 + \left[1 - \frac{3}{4}\left(\frac{k}{m_H K_1}\right)^{3/2} \mu_e \frac{\kappa_0^2}{\sigma_e^2} T_b^{-11/2}\right]^{1/2}\right\} \tag{18}$$

$$= 3.53 \times 10^{14} T_b^{3/2} \tfrac{1}{2} [1 + (1 - 1.96 \times 10^{44} T_b^{-11/2})^{1/2}] .$$

If $T_b \geq 2 \times 10^8$ the second term in the square root can be neglected and the expression for T_0^4 becomes the one for a pure scattering atmosphere. In this approximation, $(T_b/T_0)^4$ and hence the optical depth at b are both proportional to $T_b^{5/2}$, so that they decrease with decreasing T_b.

These equations permit the calculation of atmospheric properties for a sequence of values of T_b, the temperature of the isothermal core. Table 1 lists this core temperature

TABLE 1

ATMOSPHERIC PROPERTIES OF A NEUTRON STAR

T_b (° K)	T_a (° K)	ρ_b (gm cm^{-3})	T_e (° K)	λ_{max} (Å)	πF_λ ($\lambda=5$) (erg cm^{-2} sec^{-1} A^{-1})	d (pc)
2×10^9	$3\ 8\times10^7$	$4\ 3\times10^6$	$1\ 6\times10^7$	1 8	$2\ 3\times10^{31}$	1200
10^9	$5\ 0\times10^7$	$1\ 5\times10^6$	$1\ 2\times10^7$	2 4	$1\ 3\times10^{31}$	900
5×10^8	$6\ 5\times10^7$	$5\ 4\times10^5$	$9\ 4\times10^6$	3 1	$6\ 0\times10^{30}$	620
2×10^8	$9\ 1\times10^7$	$1\ 4\times10^5$	$6\ 7\times10^6$	4 3	$1\ 6\times10^{30}$	320
$1\ 19\times10^8$	$1\ 19\times10^8$	$6\ 2\times10^4$	$5\ 1\times10^6$	5 7	$4\ 4\times10^{29}$	170
10^8		$4\ 8\times10^4$	$4\ 3\times10^6$	6 8	$1\ 4\times10^{29}$	95
5×10^7		$1\ 7\times10^4$	$2\ 0\times10^6$	14	$8\ 6\times10^{25}$	2
2×10^7		$4\ 3\times10^3$	$7\ 7\times10^5$	38	$6\ 6\times10^{15}$	

T_b, the temperature T_a where scattering is fitted to Kramers' opacity, the density ρ_b where the atmosphere is fitted to the degenerate core, the effective surface temperature T_e, the wavelength λ_{max} at the maximum of the Planck function, the surface flux πF_λ at $\lambda = 5$ Å, and the distance d at which a star with this flux would produce the observed Scorpius X-ray flux. Corrections for a redshift of 0.2 are omitted. The values for ρ_b indicate that the electrons may be relativistically degenerate at the fitting boundary for the highest-temperature models.

Substitution of the ideal gas law and the explicit formula for $P(T)$ with either opacity in the hydrostatic equation for geometrical depth provides an expression for the temperature gradient in the atmosphere. Comparison of this gradient with the adiabatic one shows that there is no convection. Integration gives the geometrical height of the atmosphere; it is nearly porportional to T_b and varies from 1700 to 22 cm over the range of the table.

The distance figures in Table 1 indicate that the core of the Scorpius source cannot be cooler than 5×10^7 ° K. Since the black-body maximum is within the detector range of 1.5–8 Å, except for the last two entries, the spectrum ought to be approximately flat, as is suspected from the observations. Probably, even $T_b = 5 \times 10^7$ ° K can be eliminated on this basis. Spectral measurements at X-ray energies beyond this interval would be a useful test of whether the sources are really black bodies within the temperature range predicted here. On the other hand, at visual or ultraviolet wavelengths these stars should be undetectable. If T_b were 5×10^7 ° K and the star were as close as 2 pc its apparent photographic magnitude would be about 16, and in the ultraviolet it might be within the sensitivity of some of the orbiting astronomical observatories, but the hotter models have $m_{pg} = 23$ or fainter and are beyond the limit of any satellite telescope now planned.

IV. THERMAL ENERGY AND RATE OF COOLING

This section estimates the rate of cooling of the partially degenerate neutrons that provide the thermal energy of the neutron star. The specific heat of a Fermi gas of neutrons of mass m_n at temperature T is, according to Chandrasekhar (1939),

$$c_v = \left(\frac{\pi k}{m_n c}\right)^2 \frac{(x^2+1)^{1/2}}{x^2} T = 7.50 \times 10^{-5} XT \text{ erg gm}^{-1}, \tag{19}$$

where

$$x = \frac{h}{2 m_H c}\left(\frac{3}{\pi m_n}\right)^{1/3} \rho^{1/3} = 5.48 \times 10^{-6} \rho^{1/3} \tag{20}$$

and

$$X = \frac{(x^2+1)^{1/2}}{x^2} = 4.40 . \tag{21}$$

This value of X corresponds to the adopted mean density of 7.85×10^{14}, but it does not change rapidly with ρ. Since both ρ and T are nearly constant throughout the core, the total thermal energy E is obtained by integrating c_v from 0 to T and multiplying by the total mass. Therefore,

$$E = \tfrac{1}{2}\left(\frac{\pi k}{m_n c}\right)^2 XMT_b^2 . \tag{22}$$

Cameron (1959) estimated that the equilibrium population of electrons and nuclei associated with the neutrons contributes only 1 per cent of the density at 10^{15} gm cm^{-3}. These nuclei are less degenerate, but still they add only 2 per cent to the thermal energy. Extrapolation of the results of Hamada and Salpeter (1961) to this density suggests that the mass of non-degenerate nuclei in the outer layers is very small so that their thermal energy also can be neglected.

If L is the bolometric luminosity,

$$L = 4\pi R^2 \sigma T_e^4 = 8\pi \frac{GM}{g} \sigma T_0^4 , \tag{23}$$

and the cooling is governed by

$$L = -\frac{dE}{dt} . \tag{24}$$

Substitution of either equation (11) or equation (18) for T_0^4 in L, and the derivative of equation (22) for dE/dt gives an equation for dT_b/dt. The core temperature $T_b(0)$ when thermal cooling began is the integration constant.

If $T_b \leq 1.19 \times 10^8$ ° K, the opacity is bound-free absorption, and

$$T_b^{-9/4} = \tfrac{9}{4} \times 2.06 \times 10^{-3} \frac{\mu}{\mu_e^{3/2}} \frac{1}{\kappa_0} \frac{t}{X} + T_b(0)^{-9/4} , \tag{25}$$

while the reciprocal time for the luminosity to decrease by a factor $1/e$ is

$$\frac{1}{\tau} = -\frac{1}{L}\frac{dL}{dt} = \tfrac{17}{4} \times 2.06 \times 10^{-3} \frac{\mu}{\mu_e^{3/2}} \frac{1}{\kappa_0} \frac{T_b^{9/4}}{X} . \tag{26}$$

In the scattering approximation for $T_b \geq 2 \times 10^8$,

$$T_b^{1/2} = -\tfrac{1}{2} \times 4.29 \times 10^{-7} \frac{\mu}{\mu_e} \frac{1}{\sigma_e} \frac{t}{X} + T_b(0)^{1/2} \tag{27}$$

and

$$\frac{1}{\tau} = \tfrac{3}{2} \times 4.29 \times 10^{-7} \frac{\mu}{\mu_e} \frac{1}{\sigma_e} \frac{T_b^{-1/2}}{X} . \tag{28}$$

In this case the rate of cooling decreases with T_b because the optical depth at b also decreases. For the intermediate case with $1.19 \times 10^8 \leq T_b \leq 2 \times 10^8$, the exact equation for dT_b/dt was integrated graphically to obtain the cooling time through this interval.

For the sequence of core temperatures T_b, Table 2 lists the fourth power of the effective temperature T_e^4, the corresponding bolometric luminosity L, the total thermal energy E, the e-folding time τ for L, and the time Δt required for the star to cool from one core temperature to the next. The e-folding time for the luminosity first decreases and then increases with decreasing core temperature, following the variation of the optical depth at the core boundary, which has a minimum at the transition from electron scattering to Kramers' opacity. One per cent of this time is the time required for the luminosity to fall by 1 per cent. This variation should be observable for the cooler models in a few years if the sources are followed with well-calibrated detectors. This test would be especially sensitive if the measurements are made on the short-wavelength side of the black-body maximum where the flux decreases rapidly with temperature.

TABLE 2

THERMAL ENERGIES AND COOLING TIMES

T_b (° K)	T_e^4 (° K)	L (erg sec^{-1})	E (erg)	τ (yr)	Δt (yr)
2×10^9	6.3×10^{28}	3.9×10^{37}	1.7×10^{48}	1800	1600
10^9	2.2×10^{28}	1.4×10^{37}	4.3×10^{47}	1300	1100
5×10^8	7.9×10^{27}	4.8×10^{36}	1.1×10^{47}	920	1000
2×10^8	2.0×10^{27}	1.2×10^{36}	1.7×10^{46}	580	430
1.19×10^8	6.9×10^{26}	4.2×10^{35}	6.1×10^{45}	210	160
10^8	3.3×10^{26}	2.0×10^{35}	4.3×10^{45}	320	2200
5×10^7	1.7×10^{25}	1.1×10^{34}	1.1×10^{45}	1500	28000
2×10^7	3.5×10^{23}	2.2×10^{32}	1.7×10^{44}	12000	

At core temperatures much hotter than 2×10^9 ° K, the neutrino emission processes certainly will dominate over the radiative cooling considered here. They may be significant even down to 5×10^8 ° K. In any case no neutron star can be expected to remain hotter than 2×10^9 for more than a few years. The distance estimates of the preceding section already eliminated core temperatures less than 5×10^7 ° K for the Scorpius source. Therefore in Table 2, the sum of the intervals Δt, excluding the last one, gives a maximum age of 6800 years for this source or for any other neutron star that could be detected with present instrumental sensitivities. If the initial core temperature were only 5×10^8, as determined for the Crab source in the next section, the maximum age is only 3800 years. Shklovsky (1960) lists evidence for six supernovae within 1000 pc of the Sun during the past 2000 years. This corresponds to an average area of the galactic disk of 1.6×10^5 pc^2 per supernova remnant younger than 6800 years or a mean separation of 400 pc in the disk. A comparison with the predicted distances of the Scorpius object in Table 1 shows that they are not unreasonable for a supernova origin unless T_b is 5×10^7 ° K or less. The applicability of such low-temperature models has already been questioned because their spectra are not flat enough.

V. THE CRAB NEBULA

For this X-ray source, both its distance and time or origin are known. With assumed values for the mass and radius of a typical neutron star, it is now possible to calculate the two variable parameters of this theory, the present and original core temperatures. Shklovsky (1960) gives its distance as 1100 pc and Mayall and Oort (1942) identify it with the supernova observed by the Chinese and Japanese in A.D. 1054. As before the mass and radius are assumed to be 1.3 $M_\odot$ and 9.25 km. The observed X-ray flux of 2×10^{-9} erg sec^{-1} cm^{-2} A^{-1} at 5 Å then corresponds to a black-body effective temperature of 7.6×10^6 ° K and the bolometric luminosity is 1.5×10^{36} erg sec^{-1}. The apparent photographic magnitude is about 28, beyond the limits of detectability.

This effective temperature, combined with the assumed surface gravity by equation (18), gives a present core temperature of 2.3×10^8 ° K. Then equation (27) with $X = 4.4$ shows that the core temperature was 5.0×10^8 ° K at the start of thermal cooling, a reasonable initial value since even the most speculative neutrino processes should not cool the core much below this. The luminosity should decrease by 1 per cent in about 6 years, a little long for detection with present instrumental techniques.

It is interesting to speculate why the Crab and Scorpius sources are alike only in X-ray emission. The Crab has a visible nebula with visible and radio synchrotron radiation while the region in Scorpius shows nothing unusual in the visual or radio spectrum. All this evidence is consistent with the picture of neutron stars presented here if the visible shell and the synchrotron emission of the Crab originate from interaction of the exploding mass with a moderately dense interstellar medium containing a magnetic field. The Scorpius source is situated at a high galactic latitude in an area free of much visible nebulosity. Perhaps the interstellar medium and the magnetic field here are insufficient for a detectable interaction with the expanding remnants of the supernova.

VI. ANCIENT RECORDS OF NOVAE

Since a supernova explosion is a possible origin for a neutron star, translations of ancient astronomical records were searched for such an event in the vicinity of the position $\alpha = 16^h15^m$, $\delta = -15°$ for the Scorpius source. The most complete lists of oriental observations are those of Hsi Tse-tsung (1957) and Ho Peng Yoke (1962). Hsi lists the possible novae in the Chinese and Japanese records, while Ho includes all references to comets and novae in Chinese, Japanese, and Korean records. One has considerable confidence in the ancient observations of the Chinese because, according to Shklovsky (1960), they noted every appearance of Halley's Comet during the past 2000 years. However, it is not always possible to distinguish a comet from a nova unless the object is specifically described as moving or stationary. Some of the guest stars are definitely comets, while some of the sparkling stars, the name for comets that send out rays in all directions, must be novae. The position of any object is always related to groups of stars, usually small parts of the Western constellations. The Scorpius source is centered among several such groups: Fang, the fourth lunar mansion, which is β, δ, π, and ρ Scorpii; Kou Chhien and Chien Pi, which are ω_1, ω_2, and ν Scorpii; Tung Hsien, which is ϕ, χ, ψ, and ω Ophiuchi; and Hsi Hsien, which is ξ, 48, θ, and η Librae. A supernova coincident with the X-ray source could be associated with any one of these groups. However, reference to the description of the A.D. 1054 guest star demonstrates that the positions should not be taken too literally. The Chinese recorded its appearance southeast of Thien Kuan, which is probably ξ Tauri, but the Crab Nebula is a little more than 1° northwest of this star.

Table 3 lists five events that might be coincident with the Scorpius source. Nevertheless, none of these possible novae need be its origin; the X-ray object could have been formed by prehistoric supernovae or by some less catastrophic process.

B.C. 134, July: The Chinese recorded a guest star at Fang. This may have been the new star seen by Hipparchus, which induced him to commence his catalogue of the stars, as recorded by Pliny the Elder (A.D. 77).

A.D. 436, June 21: The Chinese recorded a sparkling star at Fang.

A.D. 827: Humboldt (1850) quotes some unspecified Arabian source: "in the reign of Caliph Al Mamoun the two famous Arabian astronomers, Haly and Giafar Ben Mohammed Albumazar observed at Babylon a new star, whose light, according to their report, equalled the moon in her quarters." It occurred in Scorpius and disappeared after 4 months. The date is no more certain than the first half of the ninth century. It is surprising that the Chinese made no record of such a spectacular object.

A.D. 891, May 11: The Japanese recorded a guest star at the east of Tung Hsien. Friedman's position is a little north and west of this group, but not far enough to eliminate this object from consideration until another flight gives better resolution. One day later, on May 12, the Chinese recorded a comet that swept from Ursa Major, through Coma, and past Arcturus into Serpens or Ophiuchus where it disappeared on July 5. The positions indicate that these were different objects, although it is difficult to understand how the astronomers of each country missed the event recorded in the other unless there is an error in one of the dates.

TABLE 3

ANCIENT NOVAE NEAR THE SCORPIUS SOURCE

Date	Observer	Star Group	Location	Brightness
B C. 134, July	Chinese	Fang	$\beta\delta\pi\rho$ Sco	
A D 436, June 21	Chinese	Fang	$\beta\delta\pi\rho$ Sco	.
A D. 827 . .	Arab	. . . .	Sco	Quarter-moon
A.D. 891, May 11	Japanese	East of Tung-Hsien	East of $\phi\chi\psi\omega$ Oph	
A.D. 1584, July 11	Chinese	Fang	$\beta\delta\phi\rho$ Sco	

A.D. 1584, July 11: The Chinese recorded that a star appeared at Fang. Lundmark (1921) notes that the meteorological records of Tycho Brahe show that he was on a journey at this time so that he may not have recorded it.

Kepler's nova of October 10, 1604, was at $\alpha = 17^{h}28^{m}$, $\delta = -21^{\circ}26'$, well outside the uncertainty of the Scorpius position. However, there is no lack of possible supernovae in the region if a recent one is required to form the X-ray source. Further research into the historical records of these events would be most worthwhile.

VII. SUMMARY

This paper has considered neutron stars as the sources of the observed X-ray emission from Scorpius and the Crab Nebula. Such a degenerate star could be formed with an interior temperature of 10^8 to 10^9 ° K, either from a supernova explosion or from the gradual contraction of an exhausted red giant whose mass slightly exceeds the white-dwarf limit. The fitting of a non-degenerate atmosphere to a neutron star of typical mass and radius demonstrated that the opacity reduces the effective surface temperature to the order of 10^7 ° K. If this star radiates like a black body it would produce the observed Scorpius X-ray flux at a reasonable distance of 10^2–10^3 pc, while remaining undetectable at visual or ultraviolet wavelengths. Calculation of the internal thermal energy has shown that the cooling time is several thousand years, long enough that a few neutron stars of supernova origin could be within the above distances.

Application of the theory to the measurements for the Crab Nebula, whose distance and age are known, gave an effective temperature of 7.6×10^6 ° K, and core temperatures of 2.3×10^8 ° K at present and 5.0×10^8 ° K initially, when the thermal cooling began. The visible nebula and the synchrotron emission are explained as the result of the interaction between the expanding shell and the interstellar medium.

More accurate calculations may change the numbers presented here, but it is unlikely that they can affect the essential conclusion that, if neutron stars exist with central temperatures of 10^8 or 10^9 ° K, they could provide the observed X-ray fluxes.

Several critical observations could be made to test whether the X-ray sources are neutron stars radiating as black bodies at temperatures of the order of 10^7 ° K. Since neutron stars are point sources, it is desirable to improve the angular resolution of the detectors as much as possible to lower the limits on the diameters of the X-ray objects. For example, it is desirable to learn if the Crab source is smaller than the 6′ diameter of the nebula. Evidence for such a hot black body requires measurements beyond the present 1.5–8-Å range which gives little spectral information because it includes the maximum of the Planck function. In making a comparison with the theory, it may be necessary to allow for spectral features due to particular elements. Finally the theory predicts that the sources are decreasing in luminosity by 1 per cent in a few years. Although this effect is probably beyond detection with present techniques, careful monitoring is desirable to test for any radical departure from this cooling rate. These observations would be most sensitive at wavelengths shortward of the black-body maximum. If no X-ray source is found which satisfies all of these criteria, the arguments of this paper may be inverted to prove that hot neutron stars do not exist, at least within the distances calculated in Table 1.

Since the Scorpius source may be the remnant of a supernova explosion, ancient astronomical records were searched for new stars in that part of the sky. Five candidates were found, B.C. 134, A.D. 436, A.D. 827, A.D. 891, and A.D. 1584, although some of these may have been comets or ordinary novae. A more accurate position for the source might eliminate its proximity to some of these events.

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