THE X-RAY EMISSION OF NEUTRON STARS

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Résumé. — *A plusieurs modèles d'étoiles à neutrons de température centrale comprise entre* 2 10^9 *et* 2 10^7 ^oK, *on a ajouté une atmosphère grise simple pour calculer l'émission de rayons X et le temps de refroidissement. Une étoile à neutrons de température centrale supérieure à* 5 10^7 ^oK *émetterait dans ces conditions assez de rayons X pour rendre compte de l'émission X observée dans le Scorpion. Des modèles d'atmosphères plus compliqués, comportant le bord d'absorption K du carbone de l'azote, de l'oxygène et du néon ont été construits pour des températures effectives de* 10^7 *et* 5 10^6 ^oK.

Abstract. — *A simple gray atmosphere has been fitted to a sequence of neutron star models with central temperatures ranging from* 2×10^9 *to* 2×10^7 ^oK *in order to estimate the X-ray emission and cooling times. A neutron star with a central temperature hotter than* 5×10^7 ^oK *would emit sufficient X-radiation to account for that observed in Scorpius. More detailed atmospheric models including the K absorption edges of carbon, nitrogen, oxygen, and neon were constructed for effective temperatures of* 10^7 *and* 5×10^6 ^oK.

Резюме. — К многим звездным моделям из нейтронов с центральной температурой заключенной между 2.10^9 и 2.10^7 ^{o}к, прибавлена простая серая атмосфера для вычисления эмиссии лучей X и времени охлаждения. Нейтронная звезда с центральной температурой превышающей 5.10^7 ^{o}к будет излучать, в этих условиях достаточно лучей X, чтобы обьяснить эмиссию X наблюдаемую в Скорпионе. Более сложеные атмосферные модели, содержащие край поглощения к углерода, азота, водорода и неона, были построены для эффективных температур 10^7 и 5.10^6 ^{o}к.

To explain the Scorpius X-ray source found by Bowyer, Byram, Chubb, and Friedman (1964), it is necessary to postulate an object that radiates soft X-rays but no significant visual or radio energy. Chiu (1964) has suggested such a source, a neutron star with a surface temperature about 10^7 ^oK radiating as a black body. The neutron star is a possible terminal phase of stellar evolution in which the interior has contracted to nuclear densities causing the nuclei to capture electrons and become neutrons in a degenerate state. A series of models by Cameron (1959) indicates a mass limit of about one Sun and a radius of some 10 km. Chiu has argued that a supernova explosion could leave a neutron core with a temperature of the order of 10^9 ^oK but not much hotter because of rapid cooling due to neutrino processes.

This paper reports some calculations of the atmospheric properties of a neutron star to determine the surface temperature and cooling time. A typical model is assumed with a mass of 1.3 Suns and a radius of 9.25 km, corresponding to a central density of 1.5×10^{15} g cm^{-3} and a surface gravity of 2.0×10^{14} cm s^{-2}. Hamada and Salpeter (1961) have shown that a neutron star is surrounded by a layer of ordinary degenerate electrons and non-degenerate nuclei. The atmosphere of non-degenerate particles was fitted to this at equal electron pressures. The high conductivity of the degenerate particles must keep the interior nearly isothermal.

In the atmosphere the opacity is due to electron scattering and bound-free absorption. The latter was represented by

$$\varkappa = 1.4 \times 10^{25} \rho^{1/2} T^{-7/2} \text{ cm}^2 \text{ g}^{-1},$$

which fits moderately well the Keller-Meyerott (1955) table for a mixture of elements heavier than helium. The transfer equation and the hydrostatic equation were combined with the ideal gas law and the above opacities to obtain the model atmosphere. In order to obtain a simple analytic solution the atmosphere was separated into an upper layer where bound-free absorption dominated and a lower layer of electron scattering. For a sequence of core temperatures T_c, Table I lists the effective temperature T_e and the distance d at which the neutron star would give the observed Scorpius X-ray flux of 1.4×10^{-8} erg s^{-1} cm^{-2} Å^{-1} at 5 Å, assuming a black-body spectral distribution. λ_{max} is the wavelength at the maximum intensity. Such a star would be undetectable at visual wavelengths.

https://doi.org/10.1017/S0074180900179653 Published online by Cambridge University Press

TABLE I

PROPERTIES OF A TYPICAL NEUTRON STAR

$M = 1.3\ M_{\odot}$; $R = 9.25$ km ; $g = 2.0 \times 10^{14}$ cm s^{-2} ; $\rho_c = 1.5 \times 10^{15}$ g cm^{-2}.

T_c °K	T_e °K	λ_{max} A	d psc	L erg s^{-1}	E erg	Δt yr
2×10^9	1.6×10^7	1.8	1200	3.9×10^{37}	1.7×10^{48}	1600
10^9	1.2×10^7	2.4	900	1.4×10^{37}	4.3×10^{47}	1100
5×10^8	9.4×10^6	3.1	620	4.8×10^{36}	1.1×10^{47}	1000
2×10^8	6.7×10^6	4.3	320	1.2×10^{36}	1.7×10^{46}	430
1.19×10^8	5.1×10^6	5.7	170	4.2×10^{35}	6.1×10^{45}	160
10^8	4.3×10^6	6.8	95	2.0×10^{35}	4.3×10^{45}	2200
5×10^7	2.0×10^6	14	2	1.1×10^{34}	1.1×10^{45}	28000
2×10^7	7.7×10^5	38	—	2.2×10^{32}	1.7×10^{44}	

Unless the neutron star is the nearest neighbour of the Sun, its core must be as hot as 5×10^7 °K. Even this cool model probably should be eliminated because its X-ray spectrum would be very weak in the shorter wavelengths of the detector bandwidth, contrary to the observations.

The available thermal energy E of the star was calculated from the expression for the specific heat of a Fermi gas of neutrons. Equating the luminosity L to the rate of change of the thermal energy $\frac{dE}{dt}$ gave the time Δt for the core temperature to cool from one entry to the next in the table. Thus a neutron star could remain detectable for a few thousand years. Such a time scale, and a distance of 100 pc or more for the Scorpius source are not inconsistent with the relatively high galactic supernova rate of 1/30 yr^{-1} suggested by SHKLOVSKY (1960).

These results demonstrate that if a hot neutron star exists within some 1000 pc, it could emit X-rays of the intensity observed in Scorpius while remaining invisible at longer wavelengths. A detailed report of this investigation is contained in a paper submitted to the *Astrophysical Journal* (MORTON, 1964).

More detailed atmospheric calculations, made in collaboration with Steven ORSZAG of Princeton have included the variation of the absorption coefficient with wavelength due to the K absorption edges of carbon, nitrogen, oxygen, and neon as well as the constant electron scattering. These edges were located at 25.6 Å, 18.6 Å, 14.2 Å, and 9.1 Å respectively. Models with flux constant throughout the atmosphere to within 3 to 5 % were constructed for effective temperatures of 10^7 °K and 5×10^6 °K. In the hotter model electron scattering dominated so that the absorption edges gave no more than a 10 % discontinuity in the flux, while in the cooler model the oxygen edge was about 25 %. Otherwise, the spectral distributions in both models closely approximated black bodies.

Manuscrit reçu le 20 *août* 1964.

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