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SURFACE X-RAY EMISSION FROM NEUTRON STARS

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Galactic x-ray emission has been observed from rockets[1] and recently[2] two discrete sources of x rays in the wavelength region of 1.5 to 8 Å have been found. The measured flux over this wavelength region was 10^{-7} erg/cm^2 sec for the stronger source (located near Scorpius) with an angular size less than 5°. The other source is about eight times weaker and seems to coincide with the Crab Nebula. The Crab is known to be the remnant of the supernova in A.D. 1054, three thousand light years away. The stronger Scorpius source may[3] be a (somewhat closer) supernova remnant of similar age.

During a type I supernova explosion, the core of the original star may contract into a hot "neutron star." Such neutron stars were suggested[4] as possible x-ray sources and we give analytic estimates[5] of their observable surface properties as a function of age (for central temperatures of the order of 10^9 °K).

Neutron stars can exist with masses between about $0.2M_\odot$ and $1.5M_\odot$ ($M_\odot = 2\times10^{33}$ g is the solar mass) and have a radius R close to 10 km and interior densities a few times 10^{14} g/cm^3. The neutrons are highly degenerate for central temperatures $T_c \ll 5\times10^{11}$ °K and their average Fermi energy $E_{\mathrm{F},n}$ is about 50 MeV. Because of the high conductivity, the neutron core is essentially isothermal and its total thermal energy E_t is[6] approximately

$$E_t = 7.6\times10^{47}(T_c/10^9\,°\mathrm{K})^2(M/M_\odot)\times(E_{\mathrm{F},n}/50\ \mathrm{MeV})^{-1}\ \mathrm{ergs}. \quad (1)$$

The neutrons are in equilibrium with a small amount of protons and electrons with $E_{\mathrm{F},n} \approx E_{\mathrm{F},e}$ ($E_{\mathrm{F},p}$ is small). Neutrinos can be emitted by a modified "Urca process" in which two neutrons with suitable momenta (near the Fermi momentum) "scatter" into a final state of $n+p+e^-+\bar{\nu}$ (the inverse process releases ν). Our present[7] estimate for this Urca energy loss rate, $L_{\nu,\mathrm{Ur}}$ is

$$L_{\nu,\mathrm{Ur}} \sim 2\times10^{36}(T_c/10^9\,°\mathrm{K})^8(E_{F,n}/50\ \mathrm{MeV})^{-2.25}\times(M/M_\odot)\ \mathrm{erg/sec}. \quad (2)$$

At densities below 10^{11} g/cm^3, the equilibrium configuration favors "ordinary ionized matter" which constitutes a thin mantle (~1 km) around the neutron core. Throughout most of the mantle the electrons are relativistically degenerate with a high conductivity, so that the temperature is close to T_c, and one can calculate the "density scale-height" analytically. The plasma neutrino process[8] has a maximum rate at densities near $(T/10^9\,°\mathrm{K})^3\times4\times10^{10}$ g/cm^3 and we find for the integrated energy loss rate $L_{\nu,\mathrm{pl}}$

$$L_{\nu,\mathrm{pl}} \approx 2\times10^{36}(T_c/10^9\,°\mathrm{K})^{10}(R/10\ \mathrm{km})^4\times(M/M_\odot)^{-1}\ \mathrm{erg/sec}. \quad (3)$$

When $\rho < \rho_m \approx (T/10^9\,°\mathrm{K})^{1.5}\times10^6$ g/cm^3, the electrons become nondegenerate and their conductivity low. The main temperature gradient then occurs in an outer nondegenerate layer (a few meters thick) of "ordinary matter." We assume $T = T_c$

at $\rho=\rho_m$, a constant opacity κ ($\kappa^{-1}\rho^{-1}$ is the photon mean free path), and $A/Z=2$ in this layer, and obtain its structure analytically. The photon luminosity $L_{\rm ph}$ is then

$$L_{\rm ph}=1.6\times10^{37}(0.2/\kappa)(M/M_\odot)\times(T_c/10^9\ {}^\circ{\rm K})^{1.5}\ {\rm erg/sec}, \qquad (4)$$

independent of the radius R. For $T_c\gtrsim5\times10^8\ {}^\circ$K, Thomson scattering of photons by free electrons dominates which gives $\kappa=0.2$. For $T_c\lesssim2\times10^8\ {}^\circ$K the opacity κ depends on temperature (roughly as $\rho^{0.5}T^{-3.5}$), due to photon absorption by a small admixture of bound electrons. We estimate an average value of 0.4 for κ at $T_c=2\times10^8\ {}^\circ$K.

Table I gives our results for several values of the central temperature for mass $M=0.5M_\odot$ and radius $R=10$ km. T_e is the effective blackbody surface temperature corresponding to $L_{\rm ph}$ and the surface area $4\pi R^2$; λ_W is $hc/4.965kT$, the wavelength of the Wien displacement law but with a gravitational red shift of 8 % included; τ is $E_t(L_\nu+L_{\rm ph})^{-1}$, a measure of the cooling time. A neutron star with $T_c\approx10^9\ {}^\circ$K in the Crab Nebula (age ~ 10^3 years) would produce near the earth, according to Table I, an x-ray intensity close to that observed.[2] This agreement is gratifying but in view of the large numerical uncertainties[9] in Table I may still be fortuitous.

Spectral measurements of discrete x-ray sources in the future will be very useful: At short wavelengths ($\lambda\lesssim1$ Å) the rapid fall-off of the neutron star's blackbody spectrum should be easy to distinguish from the flatter spectra expected from other[10] types of x-ray sources. If finer spectral resolution is available, intensity discontinuities may be detectable at wavelengths λ_K corresponding to K-shell absorption edges of medium-size nuclei (e.g., 6.3 Å for Mg and 1.3 Å for Fe, before applying the red-shift correction). Measurement of λ_K (or of absorption lines) would furnish a value for the gravitational red-shift and hence for M/R for the neutron star.

For x-ray wavelengths $\lambda\lesssim5$ Å, absorption by interstellar gas is small even across the whole galactic disc. If x-ray detection sensitivity can be improved by a factor of about 100 over that in previous flights,[1,2] then any supernova explosion which produced a neutron star during the last one or two thousand years could be detected. There could have been up to about 20 such events. Much older neutron stars with $T_e\lesssim10^6\ {}^\circ$K would be difficult to detect as x-ray sources because of strong absorption at $\lambda\lesssim30$ Å by interstellar gas. Because of its small radius the energy radiated directly in visible light by a neutron star ($L_{\rm vis}\lesssim4\times10^{27}$ erg/sec $=10^{-6}L_\odot$) is far too small to be detected in most cases. If the star is situated in a gas cloud (density $\gtrsim20$ atoms per cm^3) it will ionize a surrounding region (of radius ~0.2 light years for $T_e=10^6\ {}^\circ$K; ~0.6 light years for $T_e=10^7\ {}^\circ$K). Recombination of the ions results in visible light and the region's surface brightness may be (just barely) detectable by terrestrial optical telescopes.

The chemical composition of the atmosphere of a neutron star is uncertain at the moment, partly because the density scale-heights are so small and diffusion[11] can be much more important than in ordinary stars; H and He from the surface can diffuse in a few years to deeper layers ($T\gtrsim5\times10^8\ {}^\circ$K) where they are burned up rapidly and these two elements should be completely absent in neutron stars. The equivalent diffusion time for ^{12}C is about 100 years and C is probably strongly (but not completely) depleted in a neutron star about 1000 years old, O and Ne depleted slightly, and any Mg or heavier nuclei (present at the formation of the neutron star) are unburnt. Diffusive separation can lead in a few hundred years to a strongly enhanced abundance in the photosphere of the lightest nuclei (O, Ne, or Mg), unless convection restores mixing, in

Table I. Emission characteristics.

Core temp. T_c (°K)	Total thermal energy E_t (ergs)	Neutrino loss rate $L_{\nu'{\rm pl}}+L_{\nu'{\rm Ur}}$ (ergs/sec)	Photon luminosity $L_{\rm ph}$ (ergs/sec)	Surface temp. T_e (°K)	Cooling time τ (years)	Optimum wavelength λ_W (Å)
2×10^9	1.6×10^{48}	4×10^{39}	2.3×10^{37}	1.3×10^7	10	2.4
1×10^9	4×10^{47}	5×10^{36}	8×10^{36}	1.0×10^7	1×10^3	3.1
5×10^8	1×10^{47}	8×10^{33}	3×10^{36}	8×10^6	1×10^3	3.9
2×10^8	1.6×10^{46}	1×10^{29}	3×10^{35}	4.5×10^6	1.5×10^3	6.8

which case the metals near ^{56}Fe could be most abundant.

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[1]H. Gursky, R. Giacconi, F. R. Paolini, and B. Rossi, Phys. Rev. Letters 11, 30 (1963).

[2]S. Bowyer, E. T. Byron, T. A. Chubb, and H. Friedman (to be published).

[3]Two Arab astronomers, Haly and Albumazar, observed a very bright star, located near this x-ray source, for four months around A.D. 827. They report a brightness "comparable with the quarter moon," which is brighter (and therefore probably closer) than the original Crab explosion. However, no Chinese or Japanese records have been found yet to corroborate this event.

[4]H. Y. Chiu, Ann. Phys. 26, 364 (1964).

[5]Such estimates were first made by R. Stabler (Ph.D. thesis, Cornell University, 1960, unpublished), but he used too large a value for the effective opacity.

[6]S. Chandrasekhar, An Introduction to Stellar Structure (Dover Publications, New York, 1951), Chap. 10.

[7]This estimate is essentially the result of a dimensional analysis and could be in error by several orders of magnitude.

[8]B. Adams, M. Ruderman, and C.-H. Woo, Phys. Rev. 129, 1383 (1963). Other neutrino processes give a rate a few orders of magnitude below those discussed in this paper.

[9]For fixed T_c, our $L_{\rm ph}$ could be in error by factors of 4 or 5 and T_e by factors of about 1.5. L_ν (and hence the cooling time τ) is uncertain by larger factors. D. Morton (unpublished) has made independent estimates of T_e (but not of τ) which agree well with ours.

[10]G. W. Clark, M. Oda, and P. Morrison (unpublished).

[11]E. Schatzman, White Dwarfs (North-Holland Publishing Company, Amsterdam, 1957).

ENERGY TRANSFER PHENOMENA IN LIQUID HELIUM

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The occurrence of scintillation from liquid helium arising from ionizing radiation is now well established.[1,2] Recent studies have demonstrated that the intensity of light emitted per alpha particle seems to decrease by about 10% when the temperature is lowered below the lambda point.[3,4] During an investigation of this interesting effect, we have observed impurity emission from liquid helium in the visible optical region. These observations are of considerable interest and will be reported in the present note.

We have carried out a spectroscopic study of the light emitted from liquid helium bombarded by alpha particles. Scintillation light was produced by a 50-mCi ^{210}Po α source immersed in liquid helium. The total light emission was monitored by a detector above the liquid helium Dewar. Part of the light passed through a LiF window above the helium into the entrance slit of a vertically mounted $\frac{1}{2}$-meter McPherson Seya-Namioka vacuum spectrometer. The light detectors were EMI 9514B photomultiplier tubes coated with sodium salicylate. The spectrometer was sensitive in the region 1200 Å (the LiF cutoff) to 6000 Å, while the monitor detector was sensitive to much shorter wavelengths.

The following observations were recorded:

(1) Emission was observed from pure liquid helium (liquefied and transferred to the cryostat under standard purity precautions), but could not be detected by the spectrometer. This is consistent with the emitted light having wavelengths shorter than 1200 Å.[1] However, if the emission were in the region 1200 to 6000 Å and spread over a range of wavelengths, the spectrum would have been too weak to detect.

(2) The total light emission increased by about two orders of magnitude when the liquid helium was exposed to the atmosphere or when small amounts of oxygen and nitrogen were externally introduced into the helium.[5] Analysis of the emission spectrum established the presence of emission lines due to O_2 and N_2. This observation supports an energy transfer mechanism, in which the liquid helium absorbs most of the energy from the α particles and transfers some of it to the nitrogen and oxygen. Since their solubility in liquid helium is expected to be negligible, the possibility of energy transfer to colloidally dispersed nitrogen and oxygen cannot be excluded.

(3) Neither commercially pure liquid nitrogen nor liquid nitrogen containing dissolved oxygen