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γ-ray Lines from Accreting Neutron Stars

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Summary. The gravitational energy of an ion at the surface of neutron star is ~ 100 MeV/nucl. Therefore infalling ions may induce nuclear reactions in the external layer of the star. The γ-ray line emission produced by this process in accreting X-ray sources is evaluated in terms of the X-ray flux, assuming that the infalling matter and the stellar atmosphere have universal abundances. It is found that the most important reactions are inelastic scattering p, He and symmetrically α, H. These interactions lead to two processes yielding γ-rays, a) neutron production and capture by ambient hydrogen with emission of 2.2 MeV photons, b) direct helium excitation giving 22.5 MeV γ-rays. Pair production by these photons and consequent positron annihilation is the most important source of the 0.511 MeV line. If SCO X1 were an accreting neutron star the intensities of the lines would be $I_\gamma(2.2\,\mathrm{MeV}) \approx 2 \times 10^{-6}$, $I_\gamma(22.5\,\mathrm{MeV}) \approx 8 \times 10^{-7}$, and $I_\gamma(0.511\,\mathrm{MeV}) \approx 10^{-7}$ ph/cm^2 s.

Key words: neutron stars – accretion – X-ray sources – γ-ray lines

Introduction

Accretion of a neutron star is supported to be the mechanism of X-ray production in a number of binary systems (e.g. Her X1, Cen X3). The energy of free fall of an ion at the surface of the star is $E_i \approx 135(M/M_\odot)/R_6$ MeV/nucl, where $M/M_\odot$ is the mass of the star in solar masses and R_6 is its radius in units of 10^6 cm. The largest part of this energy is thermalized and emitted as X-rays, the details of the process being as yet under investigation. However, a fraction of the ions produce nuclear reactions yielding γ-rays which in part are emitted by the star (e.g. Schwartzman, 1972).

Ramaty *et al.* (1973) considered this process, and suggested that the observation of γ-ray lines could be a way of testing directly the composition of the neutron star surface. The flux of several nuclear lines was computed assuming that the target layer of the star was a mixture of C, N and O.

We examine the more realistic case in which the external layer (~ 50 g/cm^2) follows essentially the composition of the infalling matter, which is supposed to have a cosmic abundance.

Range of Infalling Ions

The infalling ions can produce nuclear γ-rays by excitation of nuclei in a layer whose depth is equal to the range, or indirectly through neutron production and consequent neutron capture. The range of a particle of mass Am_p and charge ze in a plasma is given by (e.g. Sivukhin, 1966),

$$l = \frac{m_e}{4\pi A z^2 e^4 L} E_i^2 \qquad (1)$$

where m_e is the electron mass, E_i is the kinetic energy of the infalling particle and L is the Coulomb logaritm, $L \approx 24.4 - \frac{1}{2}\ln n + \ln(kT)_{\mathrm{eV}}$. The number density of ambient electrons $n(\mathrm{cm}^{-3})$ can be estimated assuming that hydrostatic equilibrium is realized, (see for a discussion Zeldovich and Shakura, 1969). Therefore, one has

$$n(x) \approx \frac{2GMx}{3R^2kT}$$

where x is the depth in g/cm^2. Taking $M = 1 M_\odot$, $R = 10^6$ cm, and $kT = 5$ keV, one obtains $n \approx 10^{23}$ cm^{-3} for $x \approx 10$ g/cm^2, and the range of a proton is $l \approx 6 \times 10^{-4}$ $(E_p/\mathrm{MeV})^2$ g/cm^2; for $E_p = 135$ MeV, $\ell = 11$ g/cm^2. The dependence of energy on depth derives from Eq. (1),

$$E_p(x) = E_p(0)\left(1 - \frac{x}{\ell}\right)^{1/2}. \qquad (2)$$

We note that α-particles stop at the same depth as protons, whereas for heavier ions the range is proportional to z^{-1}. In the previous discussion we have neglected the contribution of plasma collective effects in the deceleration of the infalling particles. In the following we will come back to this point.

Composition of the Atmosphere

The production rate of nuclear γ-rays depends critically on the chemical composition of the last 10–20 g/cm^2 of the accreting star, since the range was shown to be of this order of magnitude.

The problem of the composition of the atmosphere of a neutron star has not yet been studied in detail in the case of accretion. However Rosen (1968) has investigated the temporal evolution of an external layer of 2.4×10^{13} g of hydrogen at a temperature $T = 2 \times 10^7$ °K enveloping a neutron star. The time scale in which the mass of hydrogen in the layer is reduced because of diffusion and nuclear burning was found to be $\sim 10^4$ s. Therefore it seems that the external layer of an accreting neutron star should reproduce the composition of infalling matter for accretion rates $dM/dt \gtrsim 10^9$ g/s corresponding to a luminosity $L_X = (GM/R)dM/dt \gtrsim 10^{29}$ erg/s. We note that this condition seems to be satisfied also by a neutron star accreting the interstellar matter. In this case the luminosity is $L_X \approx 10^{32}$ erg/s (Ostriker *et al.*, 1970).

In the following we suppose that both the infalling matter and the external layer of the neutron star reproduce the universal composition.

Production of γ-rays by Nuclear Interactions

We consider only nuclear reactions induced by protons and α-particles. Nuclei with $z > 2$ can be neglected because of their small abundances and the small value of the coulombian range.

The relative importance of possible reactions produced by protons and α-particles depends on the cross-section and the composition of the absorber. Infact the probability p that a reaction occurs within the range scales as,

$$p \approx \frac{\ell \sigma \eta \xi m_p}{m_s m_{\mathrm{inf}}} \tag{3}$$

where σ is the cross-section for the considered reaction, m_s is the mass of the scattered nucleus, ξ is its weight abundance, η is the abundance of the ion in the infalling matter, m_{inf} is its mass, and m_p is the mass of the proton.

From Eq. (3) one has that the most important reactions are the inelastic scattering of the infalling protons on ambient He^4 and symmetrically the scattering of α-particles on ambient H^1, which are equally probable. These interactions lead to two distinct processes yielding γ-rays, namely neutron production and capture by ambient H^1 with emission of 2.2 MeV photons, and direct He^4 excitation.

The energy dependence of the neutron production cross-section in p, He^4 scattering adopted in the following is summarized by Ramaty and Lingenfelter (1967). The excitation level of He^4 at 22.5 MeV was observed only by Hayakawa *et al.* (1964) with protons of energy $E_p = 55$ MeV, and an energy dependence of the cross-section αE^{-1} is assumed here.

a) 2.2 MeV *Deuterium Line*

The relevant reactions for neutron production are,

$$\mathrm{He}^4(p, np)\mathrm{He}^3\,; \quad \mathrm{He}^4(p, 2pn)\mathrm{H}^2\,; \quad \mathrm{He}^4(p, 2p2n)\mathrm{H}^1$$

with a Q-value which is close to 30 MeV.

Let us discuss first the reactions where protons are falling and helium nuclei are at rest. The probability of neutron production per unit path length and per incoming proton is,

$$\frac{dp(x)}{dx} = \frac{1}{\lambda_{p,\mathrm{He}^4}(E(x))} \tag{4}$$

where

$$\lambda_{p,\mathrm{He}^4} = \frac{4m_p}{\sigma_{\eta,\mathrm{He}^4}\xi}\,.$$

We assume that the average energy of produced neutrons is $\langle E_n \rangle = \frac{1}{2}(E_p - Q)$ (e.g. Ramaty and Lingenfelter, 1967).

The distribution of thermal neutrons $q_t(x)$ arising from a source of fast neutrons dp/dx is given by the Fermi theory of neutron diffusion (e.g. Fermi, 1950). In our case one has,

$$q_t(x) = \frac{1}{2\pi} \int_0^{\ell} \frac{d\bar{x}}{\sqrt{\tau_t(\bar{x})}} \frac{dp(\bar{x})}{d\bar{x}} \exp\left(- \frac{(x - \bar{x})^2}{4\tau_t(\bar{x})} \right) \tag{5}$$

where $\tau_t(\bar{x})$ is the "thermalization age" of a neutron produced at $\bar{x}$,

$$\tau_t(\bar{x}) \equiv \int_{kT}^{\langle E_n(\bar{x}) \rangle} \lambda_{n,p}^2(E_n') \frac{dE_n'}{E_n'}$$

and $\lambda_{n,p}(E_n')$ is the mean free path for neutron-proton elastic scattering. The n, p elastic cross-sections reported by Wilson (1962) are adopted here.

The depth distribution of captures of these thermal neutrons is given by,

$$\psi_{2.2}^{(1)}(x) = \frac{1}{2} \sqrt{\frac{3}{\lambda_{n,p}\Lambda}} \int_0^{+\infty} q_t(x') \exp\left(- \frac{\sqrt{3}(x - x')}{\sqrt{\lambda_{n,p}\Lambda}} \right) dx' \tag{6}$$

which takes into account both diffusion and capture effects. For neutrons of energy $kT = 5$ keV, – which is a typical temperature of an X-ray source – $\lambda_{n,p} \approx 0.1$ g/cm^2 and the capture mean free path is $\Lambda \approx 2700$ g/cm^2. Since each capture produces one 2.2 MeV photon, Eq. (6)

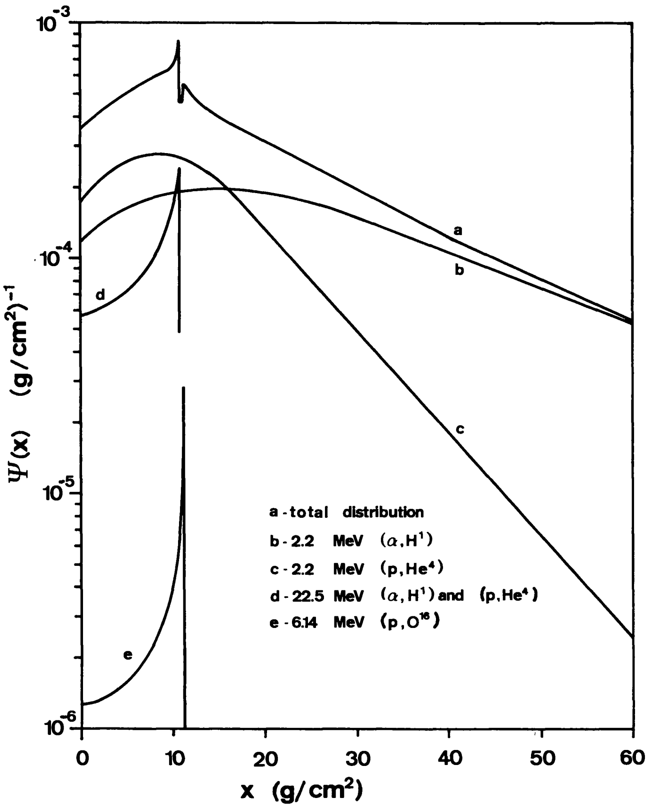

Fig. 1. The γ-ray production probability per infalling nucleon and per unit depth is shown as a function of the depth of the atmosphere of the star for the relevant nuclear reactions

gives the probability of γ-ray production per unit depth and per infalling proton. Figure 1 shows the function $\Psi^{(1)} = \tilde{\eta}_p \psi^{(1)}_{2.2}$ where $\tilde{\eta}_p \approx 0.7$ is the fraction of infalling nucleons accounted for by protons.

The computation of the contribution of 2.2 MeV γ-rays due to α, H^1 neutron production follows essentially the lines described above for p, He^4 interactions. However in this case the average energy of produced neutrons in the frame of the star is $\langle E_n \rangle = 3E/8 - Q/2$. The higher value of $\langle E_n \rangle$, and therefore the greater value of the thermalization age justifies the broader maximum of the differential probability $\Psi^{(2)} = \tilde{\eta}_\alpha \psi^{(2)}_{2.2}$ as shown in Fig. 1. $\tilde{\eta}_\alpha \simeq 0.07$ is one fourth of the weight abundance of infalling α-particles.

b) 22.5 MeV He *Line and Other Excitation Lines*

From the shape of the cross section for He excitation assumed above one can deduced the distribution $\Psi_{22.5}(x)$ of the 22.5 MeV γ-rays produced in the star atmosphere for p, He and α, H scatterings. These distributions are equal, and their sum is given in Fig. 1. Pair production by 22.5 MeV photons and consequent positron annihilation is considered in the following section.

In Fig. 1 the probability $\Psi_{6.14}(x)$ for production of 6.14 MeV photons due to the excitation of O^{16} is also given.

γ-ray Emission by an Accreting Neutron Star

From Fig. 1 it is apparent that almost all γ-rays are produced within 25 g/cm^2. Only a fraction of these photons are emitted by the star, the remainder being degraded to lower energies by Compton scattering or absorbed by photoelectric effect or pair production.

In order to study the transfer of photons within the star atmosphere, one should take into account that the amount of matter laying above the production point of a γ-ray increases with time because of accretion itself. The relevant time-scale is the mean capture time of neutrons τ_c, which is approximately given by $\tau_c \approx 1.4 \times 10^{19} \times n^{-1}$ s (Lingenfelter, 1969). For a density $n = 10^{23}$ cm^{-3} one has $\tau_c \approx 1.4 \times 10^{-4}$ s. Therefore one can neglect the increase of depth with time provided that the rate of accretion per unit area $(dM/dt)/A$ is such that $(\tau_c dM/dt)/A \lesssim 1$ g/cm^2. In the case of spherically symmetric accretion $A = 4\pi R^2$, and since $dM/dt = L_X R/GM$, the condition is fulfilled for a luminosity $L_X \lesssim L_{\max} \approx 10^{37}$ erg/s. If the neutron star is endowed with a magnetic field B, accretion occurs only at the polar caps, whose area depends on the magnetic field and the luminosity (e.g. Baan and Treves, 1973). For $B \approx 10^{12}$ Gauss, $A \approx 2.5 \times 10^{15}$ cm^2 and $L_{\max}$ is of the order of 10^{35} erg/s.

The transfer of photons has been studied for the simpler case where $L < L_{\max}$ by means of a Monte Carlo computation.

From the source functions $\Psi_{2.2}$ and $\Psi_{22.5}$ given above we obtain that the probability that an infalling nucleon gives rise to a 2.2 MeV photon escaping from the star is 1.6×10^{-3} and 6.4×10^{-4} for 22.5 MeV photons. Since each infalling nucleon has a kinetic energy ~ 135 MeV about 2.6×10^{-5} of the total luminosity is emitted in the 2.2 MeV line, and 10^{-4} in the 22.5 MeV line. 22.5 MeV photons have a non negligible probability of producing

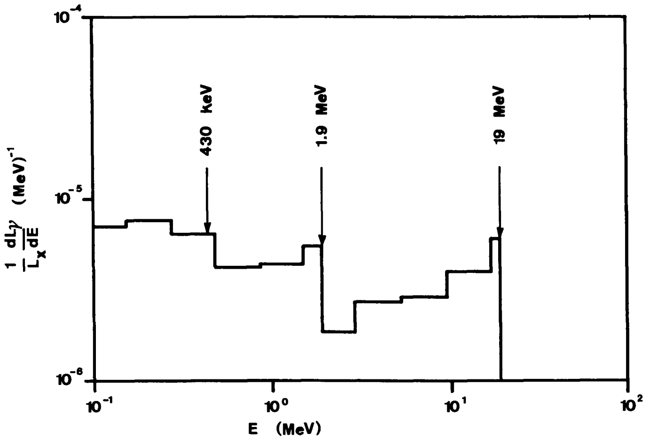

Fig. 2. Spectrum of γ-rays produced by nuclear reactions. The fraction of the total luminosity L_X emitted in the γ-ray band is given per unit energy interval as a function of the energy. The arrows represent the positions of the γ-ray lines redshifted by the gravitational field; their intensities are given in the text

electron-positron pairs before escaping from the star. Positrons can annihilate giving a pair of 0.51 MeV photons. We find that the probability of production of a 0.51 MeV photon per infalling nucleon is $\sim 2 \times 10^{-4}$. Therefore about 4×10^{-7} of the total luminosity is emitted in this line.

The photons degraded to lower energies by Compton scattering which escape from the star with $h\nu \gtrsim 100$ keV account for $\sim 10^{-5}$ of the total luminosity L_x. The spectral distribution dL/dE is given in Fig. 2 in units of L_x. In preparing the figure the effect of the gravitational redshift has been taken into account by shifting the energy scale by $\Delta E/E = GM/Rc^2 \approx 15\%$. Therefore the deuterium line should be observed at ~1.9 MeV, the helium excitation line at ~ 19 MeV and the positron annihilation line at ~0.43 MeV.

If one neglects the effects of a possible beaming of the radiation emitted by the star the ratio of the fluxes I_γ/I_x measured at Earth is equal to the ratio of the luminosities L_γ/L_x, providing a simple way of estimating the γ-ray flux expected from an X-ray source in terms of the observed X-ray flux.

Discussion and Conclusion

Our computation is subject to a number of approximations. In particular we have neglected collective plasma effects in the braking of infalling particles. If these effects were taken into account (Alme and Wilson, 1973), the range would be reduced by a factor ~6, and the γ-ray flux would be reduced at most by the same factor, since this is the only uncertainty which can affect our results in an important way.

In Table 1 we give the expected γ-ray fluxes for some strong X-ray sources which can contain accreting neutron stars. From these values, one can conclude that the fluxes of γ-ray lines are lower than those detected by present devices which are $\sim 10^{-4}$ ph/cm^{2}s. If a source were pulsed, it would be possible to increase the signal to noise ratio by a time analysis – this is usually performed in the observations of NP 0532. In our case it seems that this is not possible. In fact, as indicated by the Monte Carlo computation, the γ-rays emitted by the star are very poorly collimated, therefore the variability which is observed in the keV region in some X-ray sources and is associated with the rotation of the neutron star (time scale 1 s), would be smeared out in the γ-rays region.

Up to now, the only positive observation of non solar γ-ray line emission was reported by Johnson *et al.* (1972) who noted a feature at ~473 keV in the γ-ray spectrum from the Galactic bulge. The intensity of this line is 1.8×10^{-3} ph/cm^{2}s, corresponding to a luminosity of 10^{37} erg/s. It seems to us that this intensity cannot be explained by accretion onto neutron stars, as suggested by Ramaty *et al.* (1973). In fact the integrated luminosity of X-ray sources in the nuclear region of the Galaxy as observed by the Uhuru satellite (Giacconi *et al.*, 1972) is $\sim 10^{39}$ erg/s, and we showed that only 10^{-7} of this luminosity can be emitted in the positron annihilation line. The possibility that the observed line is produced by neutron stars accreting the interstellar medium seems also to be excluded, since it was shown (Maraschi *et al.*, 1973) that the total luminosity of such stars within ~3° from the Galactic Centre is only $\sim 10^{37}$ erg/s.

Table 1. Flux in γ-ray lines from some X-ray sources

Source	$I_x(2-6\,\text{KeV})$[a] (erg/cm^2 s)	I_γ (ph/cm^2 s) 430 KeV	1.9 MeV	19 MeV
SCO X1	3×10^{-7}	1.4×10^{-7}	2×10^{-6}	8×10^{-7}
GXG X1	2×10^{-8}	10^{-8}	1.5×10^{-7}	5.5×10^{-8}
GX 5–1	1.7×10^{-8}	8.3×10^{-9}	1.3×10^{-7}	4.7×10^{-8}
Lup X1	1.2×10^{-8}	6×10^{-9}	9×10^{-9}	3.4×10^{-8}
Cyg X2	7×10^{-9}	3.4×10^{-9}	5.3×10^{-8}	2×10^{-8}
Cen X3	2.7×10^{-9}	1.3×10^{-9}	2×10^{-8}	7.5×10^{-9}
Her X1	1.7×10^{-9}	8.3×10^{-10}	1.2×10^{-8}	4.7×10^{-9}

[a] The X-ray fluxes are derived from the UHURU catalog (Giacconi *et al.* 1972). A conversion factor between counts and fluxes $= 1.7 \times 10^{-11}$ (erg/cm^{2}s)/(count/s) has been used.

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