X-RAYS RADIATION OF A NEUTRON STAR AS A RESULT OF GAS ACCRETION

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The accretion of gas on the surface of a neutron star is a source of energy, which can be converted into X-rays radiation. Accretion can ascertain a far greater lifetime of an X-ray star than the radiation of internal energy.

The source of gas could be a cloud of intergalactic gas. If the neutron star is a component of a binary system, the gas could come from the other (non-neutronic) star.

The idea of accretion and evaluation of energetic balance were given by Zel'dovič (1964) and Zel'dovič and Novikov (1964, 1965) and Salpeter (1964). Shortly the idea of accretion was mentioned by Šklovskij (1967).

The motion of gas and radiation spectra idealised case of spheric symmetry are studied now by N. Shakuro and Zel'dovič.

As known the rate of accretion $\mathrm{d}M/\mathrm{d}t$ on the surface of a star with mass M from a gas cloud, resting at infinity with the density ρ_0 and sound velocity a_0 is given approximately by

$$\frac{\mathrm{d}M}{\mathrm{d}t} = 30\, G^2 M^2 \rho_0 a_0^{-3}.$$

The energy given per gram of the gas is $\varphi(R) = GM/R$ (R = radius of the star). For a neutron star with $M = 1{\cdot}5 M_\odot$, $R = 10^6$ cm, $\varphi(R) \sim 0{\cdot}2c^2 \sim 2 \times 10^{20}$ is far greater than the nuclear energy per gram. The luminosity L is

$$L = \varphi \frac{\mathrm{d}M}{\mathrm{d}t} = 30\, G^3 M^3 \rho_0 a_0^{-3} R^{-1}.$$

As a first approximation one could calculate the surface temperature T_c from $L = 4\pi R^2 \sigma T_c^4$; but we will prove that the radiation spectra corresponds to a higher temperature.

The flow of energy L acts upon the falling gas, repulsing it from the star. The X-rays undergo Compton scattering. The repulsion equals the gravitational attraction independent of the distance if $L = L_c = 6 \times 10^4\, M$ (Eddington's limit).

So the foregoing formula are true only in the case when they give $L < L_c$, for this it is necessary that $\rho < \rho_{0c}$. Given $T_0 = 100°$, $a_0 = 10^5$ cm/sec, M; R see above, we obtain $\rho_{0c} = 10^{-21}$ g/cm^3. At $\rho_0 > \rho_{0c}$ there is an automatic regulation of flow so that $L = L_c$.

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Below is given a detailed analysis of the case $\rho_0 < \rho_{0c}$. We take $\rho_0 = \frac{1}{3}\rho_{0c} = 3 \times 10^{-22}$ g/cm^3. Then $\mathrm{d}M/\mathrm{d}t = 3 \times 10^{17}$ g/sec $= 5 \times 10^{-9} M_\odot$/year, the radiation could last some 10^8 year before the relativistic collapse of the neutron star.

In this case $L = 6 \times 10^{37}$, $T_c = 1{\cdot}7 \times 10^7 = 1{\cdot}5$ keV. At the surface of the star the velocity of infalling gas is $U = 2 \times 10^{10}$ cm/sec, its density $\rho = 1{\cdot}2 \times 10^{-6}$ g/cm^3; $n \sim r^{-1/2}$, $\rho \sim r^{-3/2}$, $\int_r^\infty \rho \, \mathrm{d}r = 2{\cdot}4$ g/cm^2. The optical depth for Compton scattering $\tau = 1$, so the interaction of radiation with falling gas does not affect strongly the spectra and the visible diameter of the source.

The infalling gas is a stream of protons gravitationally accelerated up to energy 150–200 MeV. There is no usual shock wave. The protons strike the atmosphere of the neutron star and beat the atmosphere upon all the depth corresponding to the protons' range. Their range is of the order of $y_0 = 20$–40 g/cm^2 and depends chiefly upon nuclear scattering. Let us denote $y = \int_r^\infty \rho \, \mathrm{d}x$, y is the total mass of the atmosphere above a given point. The energy given by protons per gram of atmosphere substance, ω erg/g $\times$ sec is $\omega = Q/y_0$, $y < y_0$; $\omega = 0$, $y > y_0$, where $Q = L/4\pi R^2 = 5 \times 10^{24}$ erg/cm^2. The flow of electromagnetic radiation is given through its volume density E by

$$e \, \frac{\text{erg}}{\text{cm}^2 \times \text{sec}} = -\frac{c}{3x}\frac{\mathrm{d}E}{\mathrm{d}y}, \quad x = 0{\cdot}38 \text{ cm}^2/\text{g}.$$

Due to the independence of Compton cross-section from the energy of quanta, the formula for e is independent from the spectra of the radiation but only from the overall density E. Taking for the energy transfer from protons the first approximation, one obtains

$$e = Q\frac{y_0 - y}{y_0}, \quad y < y_0; \quad e = 0, \quad y > y_0.$$

Accounting for the condition on the top of the atmosphere, we obtain

$$y = 0, \quad E = \frac{\sqrt{3}}{2}\frac{Q}{c}$$

$$0 < y < y_0, \quad E = \frac{Q}{c}\left\{\sqrt{3} + xy_0\left[3\frac{y}{y_0} - \frac{3}{2}\left(\frac{y}{y_0}\right)^2\right]\right\}$$

$$y > y_0, \quad E = \frac{Q}{c}\left(\sqrt{3} + \frac{3}{2}xy_0\right) = 20\frac{Q}{c} = \text{const} = 3 \times 10^{15} \text{ erg/cm}^3.$$

At the depth under the layer where the protons are brought to rest, $(y > y_0)$ there is established full thermodynamic equilibrium with the temperature which can be found from

$$E = aT^4, \quad a = 7{\cdot}8 \times 10^{-15}, \quad T = 2{\cdot}5 \times 10^7, \quad y > y_0.$$

Inside the layer $(y < y_0)$ one has to calculate the balance of energy of electrons, becoming ω erg/g $\times$ sec and giving up this energy by bremsstrahlung on protons

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and by 'comptonisation, – the energy transfer to quanta by Maxwellian electrons (Kompaneec, 1955; Weyman, 1965).

$$\omega = \frac{Q}{y_0} = 5 \times 10^{20} \sqrt{T}\rho \left(1 - \frac{T'}{T}\right) + 6{\cdot}5TE\left(1 - \frac{T''}{T}\right).$$

Here T is the electron temperature, T' is a measure of (brems-)absorption of quanta by electrons in the field of protons, T'' characterises the energy given by quanta to the electrons by Compton scattering; T' and T'' depend not only from but also from the spectra of the radiation, but as a first approximation we shall assume $T' = T'' = T_r$, where $T_r = \sqrt[4]{E/a}$. The radiation density is given as a function of y above. The density is found trivially through $P = RT\rho/\mu = yg = yGM/R^2$. (The radiation pressure and the impulse of infalling protons are much smaller than the weight of the layer.)

We obtain e.g. for $y = y_0 = 30$ g/cm^2, $P = 6 \times 10^{15}$, and at $T = 2{\cdot}5 \times 10^7$, $\rho = 1{\cdot}5$ g/cm^2. The equation of energy balance is used to find the temperature of electrons T. In the case considered it varies from

$$T = 2{\cdot}6 \times 10^7 \quad \text{at} \quad y = y_0 - 0 \quad (\text{compare } T = 2{\cdot}5 \times 10^7 \text{ at } y = y_0 + 0)$$

to

$$T = 10 \times 10^7 \text{ at the top}, \quad y = 0.$$

Note that the temperature on the top does not depend in this approximation from the infalling flow of the gas and the overall luminosity L; the temperature in the depth is proportional to $\sqrt[4]{L}$.

In the layer taken as a whole, approximately one half of the energy is expended for comptonisation, the other half for bremsstrahlung.

The comptonisation markedly alters the spectrum of radiation as compared with blackbody at $T(y_0) = 2{\cdot}5 \times 10^7$. The mean energy of quanta is raised some 1·5–2 times. The difference is even more remarkable if we compare the real spectrum with the blackbody at $T_c = 1{\cdot}7 \times 10^7$.

The energy of protons in our example is slightly less than necessary for creation of pi-meson. Due to the helium content of the gas, one can anticipate some creation of pions which shall give 60 MeV quanta through $\pi^0 \to 2\gamma$ and 120 MeV through $\pi^- + p = n + \gamma$.

Now we are working on the calculation of spectrum at $\rho_0 < \rho_{0c}$; on the spherically symmetric solution for $\rho > \rho_{0c}$ where the radiation drag on the flow is important; on the stability of spheric-symmetric solutions. Further we expect to analyse the non-symmetric motion when the gas has sidewise motion or in the case of a binary.

In the case of a relativistically collapsing star it was shown previously that in the spheric-symmetric case there will be no external radiation. All the energy of the falling gas will be buried in the star. But the sidewise motion of the gas will give a shock (of the type considered by Salpeter (1964)) outside the Schwarzschild sphere, and this shock gives gamma and X-rays. We hope to investigate this problem also in details.

Note added in proof. The plasma instabilities can shorten the proton range, and increase top temperature. The amount of π^0 and gamma is diminished.

The accretion on white dwarfs was considered by Cameron (I.A.U. Trans., vol. XIII), and Cameron and Mock (1967) *Nature*, **215**, 464.

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DISCUSSION

G.G. Fazio: Have you got to a calculation on the expected intensity of gamma rays in the π_0 mechanism?

Ja.B. Zel'dovič: It is thought that it is of the order of 10^{-3} if the density is as small as 10^{-21} so that protons have energy of free fall.

P.J.A. Gaposchkin: What percent of π_0 mesons decay and what percent will interact?

Ja.B. Zel'dovič: 100% will decay and none will interact due to the very short decay time.