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HIGH-ENERGY GAMMA RAYS FROM OLD, ACCRETING NEUTRON STARS

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ABSTRACT

We consider a magnetized neutron star with accretion from a companion star or a surrounding gas cloud as a possible source of gamma rays with energies between 100 MeV and 10^5–10^7 GeV. The flow of the accreting plasma is terminated by a shock at the Alfvén surface. Such a shock is the site for the acceleration of particles up to energies of $\sim 10^6$–10^8 GeV; gamma photons are produced in the inelastic *p-p* collisions between shock-accelerated particles and accreting matter. The model is applied to old neutron stars, both isolated and in binary systems. The gamma-ray flux above 100 MeV is not easily detectable, but we propose that gamma rays with very high energy could be used by Cerenkov experiments as a possible signature of isolated, old neutron stars in dense clouds in our Galaxy.

Subject headings: accretion, accretion disks — binaries: close — gamma rays: theory — radiation mechanisms: nonthermal — stars: neutron

1. INTRODUCTION

In this paper, we study a mechanism for gamma-ray production in old, magnetized neutron stars (NSs) with accretion from a surrounding dense gas cloud or from the stellar wind of a giant companion. The NS has been supposed to have a surface magnetic field $B_S \sim 10^9$–10^{10} G, and slow rotation, so that pulsar-like activity can be neglected.

Old, isolated NSs have already been extensively studied in connection with their possible X-ray emission by Zane et al. (1995, 1996). In particular, Zane et al. (1996) found that, within a distance of 16–30 pc from Earth, ~ 10 old, isolated NSs should be present, with soft X-ray emission in the 0.2–2.4 keV band. A statistical analysis of their Galactic population has been made by Blaes & Madau (1993), who found that in our Galaxy there are $\sim 10^9$ old, isolated NSs and $\sim 1\%$ of these are in dense clouds.

The accretion of gas onto magnetized, compact objects has also been studied by many authors (see, e.g., Börner 1980) in order to obtain a description of their X-ray emission, and more specifically, the interaction of the accreting gas with the magnetic field of an NS has been investigated by Arons & Lea (1976) and Elsner & Lamb (1977), who calculated the shape of the magnetosphere and studied the way in which the plasma reaches the star's surface.

Arons & Lea (1976) claimed that a collisionless shock forms at the magnetosphere's surface. In the present paper, we consider such a shock as the site for acceleration of particles up to energies $\sim 10^6$–10^8 GeV and calculate the gamma-ray luminosity due to *p-p* collisions in the accreting gas, in the energy range between 100 MeV and 10^5–10^7 GeV.

Moreover, we investigate the possibility that 300 GeV–1 TeV gamma rays, if detectable by Cerenkov experiments, could represent a signature of old, isolated NSs in our Galaxy. This paper is arranged as follows: In § 2, the accretion is described, onto both isolated NSs and NSs in binaries; in § 3, diffusive shock acceleration theory is applied to calculate the luminosity in the form of high-energy particles at the shock around the NS magnetosphere; § 4 is devoted to the calculation of the gamma-ray flux from *p-p* collisions. Discussion and conclusions are presented in § 5.

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2. ACCRETION

In this section, we consider the accretion of matter onto a magnetized NS in two different scenarios: in the first, the NS is isolated and accretes gas from the interstellar medium (ISM); in the second, the NS is in a binary system with a giant star, and the accretion works via the stellar wind. In both cases, we shall study the role of the magnetic field in the accretion flow.

2.1. *Isolated Neutron Stars*

An isolated NS moving with velocity v with respect to the circumstellar medium having density ρ can accrete it at a rate given by the Hoyle-Littleton value:

$$\dot{M} = \pi \frac{(2GM_S)^2}{(v^2 + c_S^2)^{3/2}} \rho = 3.0 \times 10^9 v_{50}^{-3} n_1 \text{ g s}^{-1} \qquad (1)$$

(Hoyle & Littleton 1939), for a flow within the accretion radius

$$R_A = \frac{2GM_S}{v^2 + c_S^2} = 1.1 \times 10^{13} v_{50}^{-2} \text{ cm} , \qquad (2)$$

where $v_{50} = v/(50 \text{ km s}^{-1})$, $n_1 = n/(1 \text{ cm}^{-3})$, and c_S is the sound velocity in the medium. A typical value for the velocity of isolated NSs is $v \sim 10$–100 km s^{-1}, so they are always highly supersonic with respect to the medium in which they move. Thus, in equations (1) and (2), we have neglected c_S compared with v. The radius and the mass of the NS have been taken to be $R_S = 10^6$ cm and $M_S = 1\ M_\odot$. If the sound velocity c_S in the accreting gas remains appreciably smaller than the free-fall velocity, we can reasonably assume, for an ideal gas, that the accretion velocity is

$$v(r) = \xi \sqrt{2GM_S/r} , \qquad (3)$$

where $\xi \leq 1$ measures the small possible deviations from the free-fall behavior, while for the density profile it trivially follows that

$$\rho(r) = \frac{\dot{M}}{\pi \sqrt{2GM_S}} r^{-3/2} \qquad (4)$$

holds inside the accretion radius R_A, and in the assumption of quasi-spherical accretion, with a bow shock at R_A. In this expression for ρ, we have taken $\xi = 1$ (Bondi & Hoyle 1944) and dropped a factor of 4 due to the jump condition at the bow shock, usually formed at the accretion radius (this shock has been supposed to be strong, so that the compression ratio is 4).

Let us now introduce into this accretion scenario the large-scale magnetic fields, which are (1) the dipole-shaped magnetic field produced by the NS,

$$B_{\rm NS}(r) = B_S(r/R_S)^{-3} , \tag{5}$$

where B_S is the surface magnetic field of the star, and (2) the magnetic field $B_f(r)$ frozen in the accreting plasma.

During the inflow of gas toward the NS, the magnetic field lines are bent inside the plasma; this bending causes the lines to be compressed, according with the conservation of the magnetic flux,

$$B_f(r) = B_f(R_A)(r/R_A)^{-2} , \tag{6}$$

where R_A is given by equation (2). A reasonable assumption is that the magnetic field $B_f(R_A)$ at the boundary of the accretion region equals the typical ISM magnetic field, $\sim 3 \times 10^{-6}$ G. The compression of the magnetic field lines predicted by equation (6) is clearly limited by the reconnection rate; more precisely, equation (6) holds up to the point at which the hydrodynamic timescale becomes comparable to the reconnection timescale, $r/v_{\rm ff} \simeq r/v_{\rm A}$, where $v_{\rm A}$ is the Alfvén velocity and $v_{\rm ff}$ is the free-fall velocity.

The radius at which this happens is

$$r_{\rm eq} = 7 \times 10^{11} v_{50}^{-10/3} n_1^{-2/3} \text{ cm} . \tag{7}$$

When this radius is reached, reconnection compensates the increase of the magnetic field by compression, and an equipartition value is established for $B_f(r)$. Thus

$$B_f(r) = \begin{cases} B_f(R_A)(r/R_A)^{-2} , & \text{if } r_{\rm eq} < r < R_A , \\ (8\pi\rho v^2)^{1/2} , & \text{if } r < r_{\rm eq} . \end{cases} \tag{8}$$

The inflow of this magnetized plasma proceeds up to the moment at which the energy density (pressure) of the stellar magnetic field equals that of the accreting gas. The radius where this condition is fulfilled is usually referred to as the Alfvén radius, and in the following we shall denote it as R_M, according with the interpretation of this radius as the boundary of the NS magnetosphere.

Two extreme cases are possible: $r_{\rm eq} \ll R_M$ and $r_{\rm eq} \gg R_M$. In the first, at the Alfvén radius the role of the magnetic field embedded in the accreting plasma can be neglected, being much less than the equipartition value. Thus the condition for R_M is

$$\frac{B_{\rm NS}^2(R_M)}{8\pi} = \rho(R_M)v^2(R_M) . \tag{9}$$

In the second extreme case, the plasma reaches the radius R_M already in equipartition with $B_f(r)$, and equation (9) becomes

$$\frac{B_{\rm NS}^2(R_M)}{8\pi} = 2\rho(R_M)v^2(R_M) . \tag{10}$$

The exact equation, taking into account all the contributions, is

$$\frac{B_S^2}{8\pi}\left(\frac{R_M}{R_S}\right)^{-6} = \rho(R_M)v^2(R_M) + \frac{B_f^2(R_M)}{8\pi} , \tag{11}$$

where v and ρ are given by equations (3) and (4), respectively. The physical meaning of the Alfvén surface and the formation of a shock are extensively discussed by Arons & Lea (1976). The problem of describing how the accreting matter is able to reach the surface of the NS is very delicate, and no self-consistent mathematical approach exists for taking into account the several processes involved in the interaction of the gas with the magnetosphere. Nevertheless, some possibilities have been proposed: Arons & Lea (1976) and Elsner & Lamb (1977) studied the penetration of the gas through the magnetosphere by interchange instability. Börner (1980) and several other authors, mainly in connection with the problem of the X-ray emission by NSs, proposed that the plasma accretes down to the surface of the NS by being channeled along the dipolar magnetic field lines and forming an accretion column on the polar caps.

The isolated NSs that we are interested in are those located in dense environments ($n \sim 10^2$–10^8 cm^{-3}). Following Blaes & Madau (1993), in our Galaxy there should be $\sim 10^9$ isolated NSs, and ~ 1% of these are inside dense clouds. In the following, we shall consider the cases $n = 10^2$, 10^4, and 10^8 cm^{-3}, as far as the density of the cloud is concerned, and the cases $B_S = 10^9$ and 10^{10} G for the surface magnetic field of the NS. In Table 1, the values of $\dot{M}$, R_A, $r_{\rm eq}$, and R_M are reported for $B_S = 10^{10}$ G and two velocities of the NS, $v = 10$ and 80 km s^{-1}. From these numbers it results that the accreting plasma reaches the magnetosphere of the NS already in equipartition, except in the case of high-velocity NSs in very high density clouds ($n = 10^8$ cm^{-3}, $v = 80$ km s^{-1}). It is also easy to see that in these conditions the equipartition condition holds up to $v \simeq 40$ km s^{-1}. If equipartition is reached outside the magnetosphere, the radius R_M comes from equation (10):

$$R_M = 1.5 \times 10^9 v_{50}^{6/7} n_1^{-2/7} B_{10}^{4/7} \text{ cm} , \tag{12}$$

where $B_{10} = B_S/(10^{10}\text{ G})$.

In these calculations, we have neglected all effects from the rotation of the NS. This is equivalent to requiring (see Treves, Colpi, & Lipunov 1993) that (1) the relativistic wind produced beyond the light cylinder is not able to stop the accretion at the radius R_A and that (2) the accretion flow velocity at R_M is larger than the corotation velocity.

TABLE 1

Parameter Values for Accretion onto an Isolated Neutron Star for $B_S = 10^{10}$ G

	10^2 cm^{-3}		10^4 cm^{-3}		10^8 cm^{-3}	
Parameter	10 km s^{-1}	80 km s^{-1}	10 km s^{-1}	80 km s^{-1}	10 km s^{-1}	80 km s^{-1}
R_A (cm)........	2.7×10^{14}	4.3×10^{12}	2.7×10^{14}	4.3×10^{12}	2.7×10^{14}	4.3×10^{12}
$\dot{M}$ (g s^{-1})......	3.7×10^{13}	7.3×10^{10}	3.7×10^{15}	7.3×10^{12}	3.7×10^{19}	7.3×10^{16}
$r_{\rm eq}$ (cm)	6.9×10^{12}	6.7×10^{9}	3.2×10^{11}	3.1×10^{8}	6.9×10^{8}	6.8×10^{5}
R_M (cm)	1.0×10^{8}	6.0×10^{8}	2.7×10^{7}	1.6×10^{8}	2.3×10^{6}	1.4×10^{7}

Condition 1 means, for the period P of the NS, that

$$P > 1.1 B_{10}^{1/2} \left(\frac{\dot{M}}{10^{11}\ \mathrm{g\ s^{-1}}}\right)^{-1/4} \left(\frac{R_A}{10^{14}\ \mathrm{cm}}\right)^{1/8} \mathrm{s}\,,$$

while condition 2 implies

$$P > 4.9 \left(\frac{\dot{M}}{10^{11}\ \mathrm{g\ s^{-1}}}\right)^{-3/7} \mathrm{s}\,.$$

It is easy to check that these conditions are fulfilled by old, isolated NSs, for which the rotation period is usually a few seconds.

2.2. *Neutron Stars in Binaries*

We consider here a specific model for a close binary system with an NS and a giant with a stellar wind. The velocity of the wind far from the star is $v_W = 10^6$–10^8 cm s^{-1}; the rate of mass loss will be denoted by $\dot{M}_{\rm loss}$. The density of wind matter at distance r from the giant is

$$\rho_W(r) = \frac{\dot{M}_{\rm loss}}{4\pi v_W r^2}\,. \tag{13}$$

This radial outflow is appreciably influenced by the presence of the NS at a distance from it equal to the accretion radius,

$$R_A = \frac{2GM_S}{v_W^2} = 2.7 \times 10^{12} \left(\frac{v_W}{10^7\ \mathrm{cm\ s^{-1}}}\right)^{-2}, \tag{14}$$

where M_S, as usual, is the NS mass. We use here a simplified model, similar to that used in Berezinsky, Blasi, & Hnatyk (1996) (the accreting compact object was a white dwarf there), in which a bow shock forms at $\sim R_A$ and inside the shock the accretion onto the NS becomes spherically symmetric, with a density given again by equation (4), where $\dot{M}$ is now connected to $\dot{M}_{\rm loss}$ by geometric considerations. In particular, if d is the interbinary distance, we can write

$$\dot{M} \simeq \dot{M}_{\rm loss} \left(\frac{R_A}{d}\right)^2 = 7.3 \times 10^{-8} d_{13}^{-2} \left(\frac{v_W}{10^7\ \mathrm{cm\ s^{-1}}}\right)^{-4} \times \left(\frac{\dot{M}_{\rm loss}}{10^{-6}\ M_\odot\ \mathrm{yr^{-1}}}\right) M_\odot\ \mathrm{yr^{-1}}\,, \tag{15}$$

where $d_{13} = d/(10^{13}$ cm). In the following, we shall use $\dot{M}_{\rm loss} = 10^{-6}\ M_\odot$ yr^{-1}. The basic features of the accretion and of the interaction between the accreting plasma and the stellar magnetic field are the same as those previously explained for isolated NSs. However, in the case of binaries, it is more difficult to fix the boundary conditions on the magnetic field at the accretion radius, and some ad hoc assumptions about the stellar magnetic field of the companion are required. For simplicity we shall assume that, during accretion, equipartition is reached as a result of the fact that the reconnection timescale becomes comparable to the hydrodynamic timescale before the Alfvén radius is reached. Thus equation (10) holds, and we can write

$$R_M = 6.2 \times 10^6 B_{10}^{4/7} \dot{M}_{-8}^{-2/7}\ \mathrm{cm}\,, \tag{16}$$

where $\dot{M}_{-8}$ is the accretion rate in units of $10^{-8}\ M_\odot$ yr^{-1}.

In this paper, we are interested in NSs that do not show pulsar behavior, so that, in the case of binaries too, we assume that the NS rotates slowly and that its magnetic field is not greater than 10^{10} G.

The discussion, for the case of isolated NSs, about the formation of a shock due to the interaction of the accreting plasma with the magnetic wall at the boundary of the magnetosphere holds in this case, as well; in the case of binaries, it is possible that the geometry of the accretion will be modified with respect to spherical, with the formation of an accretion disk. This happens when the giant fills its Roche lobe, and the transfer of matter to the NS works by the inner Lagrangian point rather than by the stellar wind. In this situation, the simplified model used here is no longer valid, and the effect of the magnetic field should be the disruption of the internal part of the disk itself. We do not consider this case here.

3. ACCELERATION

The shock acceleration mechanism is discussed in several reviews (Jones & Ellison 1991; Blandford & Eichler 1987; Drury 1983), and we shall not stress the technical details here. We propose that the shock that is formed on the boundary of the magnetosphere of an NS, according to the mechanism described in the previous sections, can accelerate some fraction of the accreting particles up to very high energies and that the reinteraction of the accelerated particles with the gas produces a gamma-ray signal.

The shock is located at radius R_M, defined by equations (12) and (16) for the cases of isolated NSs and NSs in binaries, respectively. In the following, we discuss the two cases separately.

It is easy to estimate the luminosity in the form of accelerated particles (we assume they are protons) if we introduce an acceleration efficiency, η:

$$L_{\rm acc} = \eta \frac{GM\dot{M}}{R_M}\,. \tag{17}$$

The value usually used for η is ~ 0.1 (Berezinsky et al. 1990, p. 311). In the case of isolated NSs, by using equations (1) and (12) we have

$$L_{\rm acc}^{\rm is} = 2.6 \times 10^{26} \eta v_{50}^{-27/7} B_{10}^{-4/7} n_1^{9/7}\ \mathrm{ergs\ s^{-1}}\,. \tag{18}$$

For NSs in binaries, by equation (16),

$$L_{\rm acc}^{\rm bin} = 1.4 \times 10^{37} \eta \dot{M}_{-8}^{9/7} B_{10}^{-4/7}\ \mathrm{ergs\ s^{-1}}\,. \tag{19}$$

The maximum energy reachable by this acceleration mechanism can be calculated from the condition that the diffusion time of the accelerated particles becomes equal to the typical loss time, mainly due, in this case, to inelastic p-p collisions, whose typical cross section is $\sigma_0 = 3.2 \times 10^{-26}$ cm^2.

The diffusion time is given by

$$t_{\rm diff} = \frac{3}{u_1 - u_2} \left(\frac{D_1}{u_1} + \frac{D_2}{u_2}\right), \tag{20}$$

where subscript 2 refers to the region $r < R_M$ and subscript 1 refers to $r > R_M$. $D_i = E(\mathrm{eV})c/[300 B_i(\mathrm{G})]$ are the diffusion coefficients (we adopt here the Bohm values), and u_i are the flow velocities on the two sides of the shock. With the assumption of a strong shock, we have $u_1/u_2 = 4$, and equation (20) becomes

$$t_{\rm diff} = \frac{4 + \sqrt{2}}{75} \frac{E(\mathrm{eV})}{B_S} \frac{R_M^4 c}{2GM_S R_S^3}\,, \tag{21}$$

where we have used equation (5) for $B_2 = B_{\rm NS}(R_M)$, as well as the equipartition condition in the accreting plasma.

The typical loss time is

$$t_{\rm loss} = \frac{1}{n(R_M)\sigma_0 c} = \frac{\pi\sqrt{2GM_S}m_p}{\dot{M}\sigma_0 c} R_M^{3/2} . \quad (22)$$

The equation for the maximum energy, obtained by equating $t_{\rm diff}$ and $t_{\rm loss}$, is thus

$$E_{\rm max}({\rm eV}) = 1.1 \times 10^{40} R_M^{-5/2} B_S/\dot{M} . \quad (23)$$

This yields the results shown in Table 2 for isolated NSs (except the case shown in the last column, for which the gas reaches the magnetosphere not in equipartition), and

$$E_{\rm max}^{\rm bin}({\rm eV}) = 1.8 \times 10^{15} B_{10}^{-3/7} \dot{M}_{-8}^{-2/7} \quad (24)$$

for NSs in binaries.

The differential spectrum of the accelerated particles is taken to be $\dot{N}_p(E) = K(E + E_0)^{-\gamma}$, where the constant K is easily obtained by the condition

$$\int_{E_{\rm th}}^{E_{\rm max}} dE\, E\dot{N}_p(E) = L_{\rm acc} , \quad (25)$$

where $E_0 \sim 1$ GeV and $E_{\rm th}$ is the threshold energy for pion production in p-p collisions. The exponent γ in shock acceleration theory is connected to the compression ratio $r = u_1/u_2$ by the expression $\gamma = (r + 2)/(r - 1)$. For a strong shock, $r = 4$ and $\gamma = 2$.

From the previous discussion it results that accreting, old NSs, either isolated or in binary systems, can accelerate particles up to $\sim 10^{15}$–10^{17} eV by the shock that arises on the boundary of the NS magnetosphere. The luminosity in the form of accelerated particles, for a reference velocity of 50 km s^{-1}, is shown in Table 2.

4. GAMMA-RAY PRODUCTION

Gamma rays are produced by inelastic p-p collisions between the accelerated particles and the accreting gas. The main mechanism for gamma-ray production is the decay of the neutral pions generated by the reaction $p + p \to \pi^0 + X$. This process has been studied in detail by many authors, and the relevant cross sections, taking into account pion multiplicities, can be found in Dermer (1986).

The total number of gamma rays per unit time can be written

$$Q_\gamma = 2\frac{x}{m_p}\int_{E_{\rm th}}^{E_{\rm max}} dE\, \dot{N}_p(E)\langle\xi\sigma(E)\rangle , \quad (26)$$

where x is the grammage out of the magnetosphere and $\langle\xi\sigma\rangle$ is a multiplicity-weighted cross section for the reaction $p + p \to \pi^0 + X$ (Dermer 1986).

The real value for x could be appreciably larger than the integral of ρ onto a straight line out to some maximum distance (of the order of the accretion radius) because of the presence of the magnetic field, which is responsible for the curvature of the particles' trajectories and, therefore, for a larger column density suffered by these particles.

The integral in equation (26), if x is simply calculated by integrating over straight radial lines, is reported in Table 2, for isolated NSs, for several values of the gas density n and of the surface magnetic field. For NSs in binary systems (taking $\dot{M} = 10^{-8}\ M_\odot\ {\rm yr}^{-1}$, $d = 10^{13}$ cm), the calculation yields

$$Q_\gamma^{\rm bin} \simeq 4 \times 10^{36} B_{10}^{-6/7}\ {\rm s}^{-1} . \quad (27)$$

It is clear from Table 2 that, for isolated NSs with $v = 50$ km s^{-1} and a typical distance scale of ~ 100 pc, no gamma-ray signal can be detected in the region $E > 100$ MeV for $n = 10^2$–10^4 cm^{-3}, which is the usual range of average density in nearby dense clouds. From this point of view, giant molecular clouds (GMCs) are of particular interest: the density in their cores can reach 10^8 cm^{-3} (Turner 1988), so that the gamma-ray flux above 100 MeV becomes detectable up to a distance of ~ 800 pc. In this range of distances, many GMCs are present (see Dame et al. 1987), the closest of which is Taurus-Auriga, at ~ 140 pc. From Table 2, it can be seen that an isolated NS in the core of a GMC at such a distance should produce a signal of 10^{-6} photons cm^{-2} s^{-1} above 100 MeV. In Blaes & Madau (1993), 19 of such clouds are listed with the corresponding expected number of NSs. All are within a distance of 830 pc from Earth, and isolated NSs in their possibly very dense cores could produce a detectable gamma-ray signal with $E > 100$ MeV.

In Table 2, we also report the flux of gamma rays above 300 GeV that could be detected by a Cerenkov imaging experiment such as Whipple, whose sensitivity is $\sim 10^{-13}$ cm^{-2} s^{-1}.

While the detectability on scales of 50–100 pc from isolated NSs in a cloud with $n = 10^4$ cm^{-3} is limited to low-velocity NSs ($v \sim 10$ km s^{-1}), a signal with $E > 300$ GeV from the very dense cores of the GMCs is possible on Galactic scales ($d \sim 9$–10 kpc).

The calculation of the high-energy flux has been carried out by introducing the photon yield, Y_γ:

$$Q_\gamma(E > 0.3\ {\rm TeV}) \simeq \frac{\sigma_0}{m_p} x Y_\gamma \int_{0.3\ {\rm TeV}}^{E_{\rm max}} dE\, \dot{N}_p(E) , \quad (28)$$

where x is the grammage and $Y_\gamma \sim 0.1$; the photon yield (see Berezinsky et al. 1990, p. 320) represents the number of photons with energy E produced by one proton with the same energy that undergoes a p-p collision.

5. DISCUSSION AND CONCLUSIONS

We have studied the accretion of matter onto compact objects with surface magnetic field $B_S = 10^{10}$ G and with rotation slow enough to allow accretion and not to show

TABLE 2

PARAMETER VALUES FOR ACCELERATION AND GAMMA-RAY PRODUCTION BY p-p COLLISIONS FOR $v = 50$ km s^{-1}

	10^2 cm^{-3}		10^4 cm^{-3}		10^8 cm^{-3}	
PARAMETER	10^9 G	10^{10} G	10^9 G	10^{10} G	10^9 G	10^{10} G
$E_{\rm max}$ (eV)	3.0×10^{17}	1.1×10^{17}	8.1×10^{16}	3.0×10^{16}	6.0×10^{15}	1.6×10^{15}
$L_{\rm acc}$ (ergs s^{-1})	3.6×10^{28}	1.0×10^{28}	1.3×10^{31}	3.6×10^{30}	2.0×10^{36}	5.0×10^{35}
x (g cm^{-2})	1.1×10^{-6}	5.6×10^{-7}	2.1×10^{-4}	1.1×10^{-4}	7.8	4.0
Q_γ(>0.1 GeV) (s^{-1})	8.0×10^{21}	1.2×10^{21}	6.0×10^{26}	9.0×10^{25}	7.9×10^{36}	1.1×10^{36}
Q_γ(>0.3 TeV) (s^{-1})	8.4×10^{18}	1.2×10^{18}	6.2×10^{23}	9.7×10^{22}	4.2×10^{33}	5.8×10^{32}

pulsar-like activity. Such objects could be old NSs, for which a decrease in the surface magnetic field down to 10^9–10^{10} G has been foreseen (Phinney & Kulkarni 1994).

As a result of the interaction between the magnetic field of the star and the accreting plasma, a magnetosphere is formed around the NS, bounded by a collisionless shock (Arons & Lea 1976), where the pressure of the gas equals that due to the magnetic field of the NS. Even though the existence of such a shock has been assumed by several authors, no conclusive agreement has been reached about it, as a result of the fact that a self-consistent mathematical description of the accretion in the presence of a strong magnetic field does not exist. In this paper, we assumed the existence of the shock and proposed that it could accelerate nuclei (protons) up to high energies (see also Shemi 1995), according with the usual mechanism of diffusive shock acceleration.

These accelerated particles can produce a gamma-ray signal due to the inelastic $p + p \rightarrow \pi^0 + X$ collisions with π^0 decay in $\gamma\gamma$, where the target is provided by the accreting gas.

The luminosity in the form of accelerated particles from isolated NSs strongly depends on two parameters, the matter density around the NS and the velocity of the NS. The NSs considered here are those contained in dense clouds (there are 10^7 such objects in the Galaxy), where the gas density ranges between 10^2 and 10^8 cm^{-3} (in the cores of the GMCs). A statistical study of the velocity distribution of these NSs has been performed by Blaes & Madau (1993), who found that $\sim$6% of these objects have $v < 20$ km s^{-1}, $\sim$22% have $v < 40$ km s^{-1}, and $\sim$50% have $v < 72$ km s^{-1}.

In Table 1, we have shown the accretion parameters for $n = 10^2$, 10^4, 10^8 cm^{-3} and for two extreme velocities, 10 and 80 km s^{-1}, verifying that for old NSs the role of rotation can be neglected. In Table 2, we have shown the acceleration data and the fluences of gamma rays with $E > 100$ MeV, fixing the velocity at 50 km s^{-1} and distinguishing the cases $B_S = 10^9$ G and $B_S = 10^{10}$ G, for the usual range of densities. In particular, we also estimated the flux of very high energy gamma rays ($E > 300$ GeV) detectable by the Cerenkov experiments such as Whipple. From these data, it seems hopeless to observe with present detectors the 100 MeV radiation produced by *p*-*p* collisions in gas clouds with $n \sim 10^2$–10^4 cm^{-3}, at least for distance scales $\sim$100 pc, unless for very low velocity NSs ($v \leq 10$ km s^{-1}), which are however a very small percentage of the total.

Much more interesting is the situation of the cores of the GMCs ($n \sim 10^8$ cm^{-3}). In this case, the 100 MeV radiation is detectable at distances of 800 pc, and the very high energy part of the gamma-ray spectrum ($E > 300$ GeV) could be detected by Whipple-like experiments on Galactic scales (9–10 kpc). Many GMCs are located within such distances: the closest is Taurus-Auriga, at 140 pc, which could contain up to 30 NSs; about 300 NSs should be present in the Cygnus Rift, 700 pc away, and many other GMCs can be found within 800–900 pc (Blaes & Madau 1993; Dame et al. 1987).

Isolated NSs in the dense cores of GMCs would necessarily be bright X-ray emitters because the matter stopped at the magnetosphere's wall is later channeled to the polar caps, liberating a luminosity 2–4 orders of magnitude greater than the gamma-ray one. However, such X-rays will hardly leave the dense region, because of the strong Compton absorption. Besides, accretion of gas down to the stellar surface could be stopped, for some values of the parameters, as a consequence of the fact that low-velocity NSs in very high density environments should accrete at super-Eddington rates: radiation pressure could introduce in this case some nonstationary accretion regime. Thus gamma rays would be a unique tool for the study of isolated NSs in overdense regions. On the other hand, X-rays in the 0.2 keV region remain the most powerful way to observe isolated NSs in moderately dense clouds, where the gamma-ray flux should be too small.

Here we also discussed the case of NSs not showing pulsar-like activity in binary systems, but the conclusions reached about them are strongly parameter and model dependent. This is a consequence of two factors: First, the accretion rate onto the NS varies abruptly when the geometry of the binary is changed (e.g., interbinary distance, size of the companion), and therefore the position of the magnetic wall is also changed, and with it the luminosity in the form of cosmic rays. The second factor is that the geometry of the accretion can probably become far from spherical (disk accretion); in the case of disk accretion, the effect of the stellar magnetic field is usually to disrupt the part of the disk inside the Alfvén radius, and no shock is probably produced in this case, or at least it should be not useful for accelerating particles. Nevertheless, in the cases in which our calculation holds, the signal from old NSs in binaries can be detected by EGRET if the source is located within $\sim$500 pc from Earth.

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REFERENCES

Arons, J., & Lea, S. M. 1976, ApJ, 207, 914
Berezinsky, V. S., Blasi, P., & Hnatyk, B. I. 1996, ApJ, 469, 311
Berezinsky, V. S., Bulanov, S. V., Dogiel, V. A., Ptuskin, V. S., & Ginzburg, V. L. 1990, Astrophysics of Cosmic Rays, ed. V. L. Ginzburg (Amsterdam: North-Holland)
Blaes, O., & Madau, P. 1993, ApJ, 403, 690
Blandford, R., & Eichler, D. 1987, Phys. Rep., 154, 1
Börner, G. 1980, Phys. Rep., 60, 151
Bondi, H., & Hoyle, F. 1944, MNRAS, 104, 273
Dame, T. M., et al. 1987, ApJ, 322, 706
Dermer, C. D. 1986, A&A, 157, 223
Drury, L. O'C. 1983, Rep. Prog. Phys., 46, 973
Elsner, R. F., & Lamb, F. K. 1977, ApJ, 215, 897
Hoyle, F., & Littleton, R. A. 1939, Proc. Cambridge Philos. Soc., 35, 405
Jones, F. C., & Ellison, D. C. 1991, Space Sci. Rev., 58, 259
Phinney, E. S., & Kulkarni, S. R. 1994, ARA&A, 32, 591
Shemi, A. 1995, MNRAS, 275, 115
Treves, A., Colpi, M., & Lipunov, V. M. 1993, A&A, 269, 319
Turner, B. E. 1988, in Galactic and Extragalactic Radio Astronomy, ed. G. L. Verschuur & K. I. Kellermann (2d ed.; Berlin: Springer), 154
Zane, S., Turolla, R., Zampieri, L., Colpi, M., & Treves, A. 1995, ApJ, 451, 739
Zane, S., Zampieri, L., Turolla, R., & Treves, A. 1996, A&A, 309, 469