# 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 gas cloud around it, as a possible source of gamma rays with energy between 100 $MeV$ and $10^{13} - 10^{14}$ $eV$. 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 $\sim 10^{15}$ $eV$; gamma photons are produced in the inelastic $pp$ collisions between shock-accelerated particles and accreting matter. The model is applied to old neutron stars both isolated or in binary systems. The gamma ray flux above 100 $MeV$ is not easily detectable, but we propose that gamma rays with energy above $\sim 3$ $TeV$ could be used by Cherenkov experiments as a possible signature of isolated old neutron stars in dense clouds in our galaxy, at least for distances up to $13 - 35$ $pc$ according with a surface magnetic field of the neutron star $10^{10} - 10^9$ $G$ respectively.

*Subject headings:* acceleration: shock - stars: neutron, old, accreting - radiation: gamma

## 1.  Introduction

In this paper we study a mechanism for gamma ray production in old magnetized neutron stars (NS's) with accretion from a dense gas cloud around it, 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 NS's have already been extensively studied in connection with their possible X-ray emission by (Zane *et al.* 1995a, Zane *et al.* 1995) . In particular (Zane *et al.* 1995) found that inside a distance $16 - 30\ pc$ from the Earth, about 10 old isolated NS's should be present, with a soft X-ray emission in the $0.2 - 2.4\ keV$ band. A statistical analysis of their galactic population has been made by (Blaes and Madau 1993)  who found that in our Galaxy there are $\sim 10^9$ old isolated NS's, and about 1% of them are in dense clouds.

The accretion of gas onto magnetized compact objects has also been studied by many authors (see for example Börner 1980) in order to get a description of the X-ray emission by them, and more specifically the interaction of the accreting gas with the magnetic field of the NS has been investigated by (Arons and Lea 1976) and (Elsner and Lamb 1977) who calculated the shape of the magnetosphere and studied the way for the plasma to reach the star surface.

(Arons and Lea 1976) claimed that a collisionless shock forms at the magnetosphere surface. In the present paper we consider such a shock as the site for acceleration of particles up to energies $\sim 10^5 - 10^6\ GeV$ and calculate the gamma ray luminosity due to $pp$ collisions in the accreting gas, in the energy range between $100\ MeV$ and $10^4 - 10^5\ GeV$.

Moreover we investigate the possibility that gamma rays with energy higher than $\sim 3\ TeV$, if detectable by Cherenkov experiments, could represent a signature of old isolated NS's in our galaxy. This paper is planned as follows: in section 2 accretion is described both on isolated NS's and NS's in binaries; in section 3 the diffusive shock acceleration theory is applied to calculate the luminosity in the form of high energy particles at the shock around the NS magnetosphere; section 4 is devoted to the calculation of the gamma ray flux from $pp$ collisions. Discussion and conclusions are presented in section 5.

## 2.  The accretion

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

## 2.1. Isolated Neutron Stars

An isolated NS moving with velocity $v$ with respect to the circumstellar medium having density $\rho$ can accrete it with a rate which is given by the Hoyle-Littleton value (Hoyle and Littleton 1939):

$$\dot{M} = \pi \frac{(2GM_S)^2}{(v^2 + c_S^2)^{3/2}} \rho = 3.7 \times 10^{11} v_6^{-3} n_1 \ g/s, \tag{1}$$

for a flow within the accretion radius:

$$R_A = \frac{2GM_S}{v^2 + c_S^2} = 2.67 \times 10^{14} v_6^{-2} \ cm \tag{2}$$

where $v_6 = v/(10^6 cm/s)$ and $n_1 = n/(1 cm^{-3})$ and $c_S$ is the sound velocity in the medium. A typical value for the velocity of isolated NS's is $v \sim 10 - 100 \ km/s$, so that they are always highly supersonic with respect to the medium in which they move. Thus in eqs. (1) and (2) we 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 $M_S = 1 \ M_\odot$ respectively. 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

$$v(r) = \xi \sqrt{\frac{2GM_S}{r}} \tag{3}$$

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

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

holding 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 $\rho$ we took $\xi = 1$ (Bondi and Hoyle 1944) and we dropped a factor 4 due to the jump condition at the bow shock usually formed at the accretion radius (this shock has been supposed to be a strong one, so that the compression ratio is 4).

Let us now introduce in this accretion scenario the large scale magnetic fields that are: $i)$ the dipole-shaped magnetic field produced by the NS

$$B_{NS}(r) = B_S \left(\frac{r}{R_S}\right)^{-3} \tag{5}$$

where $B_S$ is the surface magnetic field of the star; $ii)$ the magnetic field $B_f(r)$ frozen in the accreting plasma.

During the inflow of the gas towards 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

$$B_f(r) = B_f(R_A) \left(\frac{r}{R_A}\right)^{-2} \tag{6}$$

where $R_A$ is given by eq. (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 eq. (6) is clearly limited by the reconnection rate; more precisely eq. (6) holds up to the point where the hydrodynamical time scale becomes comparable with the reconnection time scale: $r/v_{ff} \simeq r/v_A$, where $v_A$ is the Alfvén velocity and $v_{ff}$ is the free-fall one.

The radius at which this happens is given by

$$r_{eq} = 1.5 \times 10^{14} \ v_6^{-10/3} \ n_1^{-2/3} \ cm. \tag{7}$$

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

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

The inflow of this magnetized plasma proceeds up to the moment in 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: $r_{eq} \ll R_M$ and $r_{eq} \gg R_M$. In the first one, 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

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

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

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

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 $\rho$ are given by eqs. (3) and (4) respectively. The physical meaning of the Alfvén surface and the formation of a shock are widely discussed by (Arons and 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 and Lea 1976) and (Elsener and 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 NS's, proposed that the plasma accretes down to the surface of the NS being channelled along the dipolar magnetic field lines, and forming on the polar caps an accretion column.

In this paper we shall study what happens at the shock, as the site for acceleration of protons up to high energies.

The isolated NS's which we are interested in are those located in dense environments ($n \sim 10^2 - 10^8\ cm^{-3}$). Following (Blaes and Madau 1993) in our galaxy there should be $\sim 10^9$ isolated NS, and $\sim 1\%$ of these are inside dense clouds. In the following we shall use $n = 10^4\ cm^{-3}$, $v = 10\ km/s$ and $B_S = 10^{10}\ G$. Thus from the above formulae: $R_A = 2.7 \times 10^{14}\ cm$, $\dot{M} = 3.7 \times 10^{15}\ g/s$, $r_{eq} = 3.2 \times 10^{11}\ cm$. From these numbers it is clear that the gas reaches equipartition before interacting with the magnetosphere, thus eq. (10) gives

$$R_M = 3.76 \times 10^8\ B_{10}^{4/7}\ v_6^{6/7}\ n_1^{-2/7}\ cm \tag{12}$$

where $B_{10} = B_s/10^{10}G$. For $n = 10^4\ cm^{-3}$ we have $R_M = 2.7 \times 10^7\ cm$.

In these calculations we neglected all the effects coming from the rotation of the NS. This is equivalent to require that (see Treves *et al.* 1995): 1) the relativistic wind produced beyond the light cylinder is not able to stop the accretion at the radius $R_A$; 2) the accretion flow velocity at $R_M$ is larger than the corotation velocity.

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

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

while condition 2) gives

$$P > 4.9(\dot{M}/10^{11}g/s)^{-3/7}\ s.$$

For $v_6 = 1$ and $n = 10^4 cm^{-3}$ these expressions become $P > 0.09\ s$ and $P > 0.05\ s$ respectively. They are surely fulfilled by old isolated NS, for which it is usually $P > 1\ s$.

## 2.2. Neutron Stars in binaries

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

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

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

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

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

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

where $d_{13} = d/(10^{13} cm)$. In the following we shall use $\dot{M}_{loss} = 10^{-6}\ M_\odot/yr$. 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 NS's. 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 should be required. For simplicity we shall assume that during accretion the equipartition is reached due to the fact that the reconnection time scale becomes comparable with the hydrodynamical time scale before the Alfvén radius is reached. Thus eq. (10) holds, and we can write:

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

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

In this paper we are interested in NS's that do not show pulsar behaviour, so that, in the case of binaries too, we assume that the NS rotates slowly and that its magnetic field is not larger than $10^{10}\ G$.

The discussion made in the case of isolated NS's about the formation of a shock as a consequence of 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 is modified with respect to the spherical one, 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 instead 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 shall not consider this case here.

## 3. The acceleration

The shock acceleration mechanism is discussed in several reviews (Jones and Ellison 1991, Blandford and Eichler 1987, Drury 1983) and we shall not stress here the technical details. In

this paper we propose that the shock which is formed on the boundary of the magnetosphere of a 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 the radius $R_M$ defined by eqs. (12) and (16) for the case of isolated NS's and NS's in binaries respectively. In the following we shall 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 $\eta$:

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

The value usually used for $\eta$ is $\sim 0.1$ (Berezinsky *et al.* 1990) . In the case of isolated NS's in dense clouds ($n = 10^4 \ cm^{-3}$), by using eqs. (1) and (12) we have

$$L_{acc}^{is} = 1.8 \times 10^{34} \ \eta \ v_6^{-27/7} \ B_{10}^{-4/7} \ erg/s. \tag{18}$$

For NS's in binaries, by eq. (16):

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

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

The diffusion time is given by

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

where the subscript 2 refers to the region $r < R_M$ and the subscript 1 refers to $r > R_M$. $D_i = E(eV)c/300B_i(Gauss)$ are the diffusion coefficients (we adopt here the Bohm's values), and $u_i$ are the flow velocities on the two sides of the shock. In the assumption of a strong shock we have $u_1/u_2 = 4$ and eq. (20) becomes

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

where we used eq. (5) for $B_2 = B_{NS}(R_M)$ and we used the equipartition condition in the accreting plasma.

The typical loss time is

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

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

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

(23)

This gives

$$E_{max}^{is}(eV) = 7.8 \times 10^{15} \ B_{10}^{-3/7}$$

(24)

for isolated NS's with $v = 10^6 \ cm/s$ and $n = 10^4 \ cm^{-3}$, and

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

(25)

for NS's in binaries.

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

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

(26)

where $E_0 \sim 1 \ GeV$ and $E_{th}$ is the threshold energy for pion production in $pp$ collisions. The exponent $\gamma$ in the 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 NS, both isolated or in binary systems, can accelerate particles up to $\sim 10^{15} \ eV$, by the shock arising on the boundary of the NS magnetosphere. The luminosity in the form of accelerated particles for surface magnetic field $\sim 10^{10} G$ is as large as $\sim 10^{33} \ erg/s$ for isolated NS's in dense clouds, and up to $\sim 10^{36} \ erg/s$ for NS's in binaries.

## 4.  Gamma ray production

Gamma rays are produced by $pp$ inelastic 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 $p + p \rightarrow \pi^0 + X$.

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 as follows:

$$Q_\gamma = 2 \ \frac{x}{m_p} \ \int_{E_{th}}^{E_{max}} dE \ \dot{N}_p(E) \ < \xi\sigma(E) >$$

(27)

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

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

The integral in eq. (27), if $x$ is simply calculated by integrating over straight radial lines, gives:

$$Q_\gamma^{is} \simeq 1.5 \times 10^{31} \ B_{10}^{-6/7} \ s^{-1} \tag{28}$$

for isolated NS's in dense clouds, and:

$$Q_\gamma^{bin} \simeq 4 \times 10^{36} \ B_{10}^{-6/7} \ s^{-1} \tag{29}$$

for NS's in binary systems (we took $\dot{M} = 10^{-8} \ M_\odot/yr$, $d = 10^{13} \ cm$).

In both the cases the dipendence of $Q_\gamma$ on the stellar magnetic field is the same: an increase in $B_S$ causes a decrease in $Q_\gamma$, mainly as a result of the fact that the shock is moved far from the NS by the increased magnetic pressure. On the other hand, NS's with very weak surface magnetic fields $B_S \sim 10^9 \ G$, have a larger gamma ray emission: $Q_\gamma^{is} \simeq 10^{32} \ s^{-1}$ and $Q_\gamma^{bin} \simeq 10^{37} \ s^{-1}$, because now the shock is closer to the NS (see eq. (17)).

The gamma ray flux above $\sim 70 \ MeV$ from isolated NS's is too weak to be detected by the present day devices for reasonable distances on galactic scales. $Q_\gamma^{bin}$ could instead be seen by EGRET if the source is located inside $\sim 500 \ pc$ from the Earth. In both cases the spectrum of the gamma radiation has the typical bump at $E \sim 70 \ MeV$, while for $E \gg 70 \ MeV$ the spectrum is power lawered, with the same power index as the particles accelerated at the shock. The maximum energy of the gamma rays produced by this mechanism can reach $\sim 20\%$ of the maximum energy of the parent protons, thus gamma rays up to $10^{13} - 10^{14} \ eV$ could be produced. Though the 100 $MeV$ photons should hardly be detected by future experiments, the high energy part of the gamma ray spectrum ($E > 3 \ TeV$) could give a unique signature for isolated old NS's, in particular when the source is located in very dense clouds where some self-absorbtion of the possible X-ray emission can occur.

The gamma ray flux with $E > 3 \ TeV$ (suitable for Cherenkov experiments) for old isolated NS's, can be easily calculated by using $x \simeq 0.03 \ B_{10}^{-2/7} g/cm^2$ and the scaling assumption:

$$Q_\gamma(E > 3TeV) \simeq \frac{\sigma_0}{m_p} \ x \ Y_\gamma \int_{3TeV}^{E_{max}} dE \ \dot{N}_p(E) \simeq 2 \times 10^{27} \ B_{10}^{-6/7} \ s^{-1}, \tag{30}$$

where $Y_\gamma \sim 0.1$ is the photon yield (see Berezinsky $et \ al.$ 1990) ; it represents the number of photons with energy $E$ produced by one proton with the same energy which undergoes a $pp$ collision. For $B_S = 10^{10}G$ and a sensitivity for a Cherenkov experiment of $\sim 10^{-13} \ cm^{-2} \ s^{-1}$, we obtain a maximum detectability distance $\sim 13 \ pc$; this distance becomes $\sim 35 \ pc$ for $B_S = 10^9G$, which is still realistic for old isolated NS's. This sensitivity has already been reached by the Whipple experiment above 0.2 $TeV$; a future experiment whit sensitivity $10^{-14} \ cm^{-2} \ s^{-1}$ should detect these gamma rays up to a distance of $\sim 42 \ pc$ for $B_S = 10^{10}G$ and $\sim 100 \ pc$ for $B_S = 10^9G$.

## 5. Discussion and conclusions

We 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 pulsar-like activity.

Such objects could be old NS's, for which it has been foreseen a decrease in the surface magnetic field down to $10^9 - 10^{10} \ G$ (Phinney and 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 and Lea 1976), where the pressure of the gas equals that due to the magnetic field of the NS. Even if the existence of such a shock has been assumed by several authors, no conclusive agreement has been reached about it, due to the fact that a self-consistent mathematical description of the accretion in 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 the diffusive shock acceleration.

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

The luminosity in the form of accelerated particles from isolated NS's strongly depends on two parameters, the matter density around the NS, and the velocity of the NS. The results we found here, both for NS's in binaries and isolated are rather optimistic. We assumed that our isolated NS's move with velocity $v \sim 10 \ km/s$, while from statistical studies (Blaes and Madau 1993) it is known that only $\sim 6\%$ of these objects have $v < 20 \ km/s$, $\sim 22\%$ have $v < 40 \ km/s$ and $\sim 50\%$ have $v < 72 \ km/s$. Thus only a small fraction of the isolated NS's can give the result found here. Unfortunately the luminosity in the form of cosmic rays from isolated NS's goes as $v^{-27/7}$, so that it decreases abruptly when velocity increases. On the other hand we considered isolated NS's in dense clouds whose density has been fixed at $10^4 \ cm^{-3}$, even if these clouds could have densities in the range $10^2 - 10^8 \ cm^{-3}$, and the gamma ray luminosity is proportional to $n^{17/7}$. Thus very few of these objects could give a signal stronger than that obtained here.

An interesting consequence of the acceleration mechanism proposed here is the high energy to which the cosmic rays can be accelerated: we obtained for this a value of $\sim 10^{15} \ eV$ in the case of old isolated NS's, which means for the gamma rays a maximum energy of $\sim 20\%$ of this. Here we discussed also the case of NS's 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 of all 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 being 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 NS's in binaries is stronger than that from isolated NS, and it could be detected by EGRET if the source is located inside $\sim 500$ $pc$ from the Earth.

Though it seems hopeless to observe the 100 $MeV$ gamma rays produced by the $pp$ collisions in old isolated NS's with the present day detectors, some interesting possibility is provided by the Cherenkov experiments in the measure of the flux above $\sim 3$ $TeV$; a minimum detectable flux of $10^{-13}$ $photons$ $cm^{-2}$ $s^{-1}$ could allow the detection of old isolated NS's as far as their distance is up to $\sim 13$ $pc$, if their surface magnetic field is $\sim 10^{10}$ $G$, and up to a distance of $\sim 35$ $pc$ if the surface magnetic field is $10^9$ $G$.

The gamma rays with such energies could give a good alternative to the X-ray observation of these objects, in particular in the cases in which the circumstellar environment is a superdense cloud, with a possible self-absorbtion of the X-rays.

# REFERENCES

Arons , J., &Lea, S. M. 1976, ApJ, 207, 914.

Berezinsky, V. S., Blasi, P., Hnatyk, B. I. 1996, Accepted for publication in ApJ.

Berezinsky, V. S. *et al.* in 'Astrophysics of Cosmic Rays' (North Holland 1990).

Blaes, O. & Madau, P. 1993, ApJ, 403, 690.

Blandford, R. & Eichler, D. 1987, Phys. Rep., 154, 1.

Bondi, H. & Hoyle, F. 1944, MNRAS, 104, 273.

Börner, G. 1980, Phys. Rep., 60 n. 3, 151.

Dermer, C. D. 1986, A&A, 157, 223.

Drury, L. O'C 1983, Rept. Prog. Phys., 46, 973.

Elsner, R. F. & Lamb, F. K. 1977, ApJ, 215, 897.

Hoyle, F. & Littleton, R. A. 1939, Proc. Cambridge Phil. 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, accepted for publication in MNRAS.

Treves, A., Colpi, M. & Lipunov, V. M. 1993, A&A, 269, 319.

Zane, S., Turolla, R., Zampieri, L., Colpi, M. & Treves, A. 1995a, Submitted to ApJ.

Zane, S., Zampieri, L., Turolla, R. & Treves, A. PREPRINT astro-ph 9509094.