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Globular Clusters as Gamma Ray Sources

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Abstract. There are indications now that globular clusters contain a large number of low magnetic field millisecond pulsars. Since millisecond pulsars are expected to emit γ-rays due to curvature radiation, it is likely that globular clusters will themselves be sources of γ-rays bright enough to be detectable by present day instruments. Using the expression derived by Scharlemann, Arons & Fawley (1978) of the energy acquired by the electrons moving along the open magnetic field lines of the pulsars we have calculated the likely luminosity of γ-rays from globular clusters. We discuss our results in the light of the calculations reported in the literature based on some of the other models.

Key words: globular clusters—pulsars—resurrected neutron stars—γ-rays

1. Introduction

In the last few years a new population of pulsars, namely the millisecond pulsars, has been discovered. The short period of rotation makes them good candidates for emitting γ-rays. Efforts are being made to detect high energy gamma rays from these pulsars and there are already hints that very high energy γ-rays from two of these pulsars have been observed (Chadwick *et al.* 1985, 1987).

These millisecond pulsars having typically magnetic fields of the order of 10^8 G, which is characteristic of slow-rotating old pulsars, are thought to be the spun-up neutron stars. The detection of binary companions of many of these pulsars has already been confirmed. This has supported the view that the old neutron stars are spun up by mass accretion from their respective companions over a long period of time. In this way an old neutron star with a low magnetic field (~ 10^8 G) gets spun up to a resurrected period given by the mass accretion relation (Radhakrishnan & Srinivasan 1981; Alpar *et al.* 1982)

$$p \sim B_8^{6/7}(\dot{M} \times 10^8/M_\odot/\text{yr})^{-3/7}\,\text{s}, \tag{1}$$

where $\dot{M}$ is the mass accretion rate and the maximum value of M is the Eddington rate given by $M_\odot/10^8$ per year.

It has been suggested that there may be of the order of a thousand millisecond pulsars in one globular cluster (Kulkarni 1990; Manchester *et al* 1991). Already 28 millisecond pulsars have been discovered in globular clusters (Chen 1991). Though the distribution of these millisecond pulsars with period is not exactly known yet a reasonable relation has been given by Chen, which is a power law distribution:

$$F(p) = (\alpha - 1)p_{\text{min}}^{\alpha-1}\,p_{\text{ms}}^{-\alpha}, \tag{2}$$

where period is in millisecond, $\alpha = 1.4$ for $p_{ms} > p_{min}$ and the minimum value of period p_{min} is 1.6 ms.

A globular cluster containing a large number of resurrected millisecond pulsars which emit gamma rays is likely to be itself a source of gamma rays. In this paper we discuss a model which gives an estimate of γ-luminosity of a globular cluster. In section 2, we present the model and an estimate of the luminosity of a globular cluster which contains the millisecond pulsars. In section 3 we compare our results with those derived on the basis of some other models.

2. Model and its prediction

The magnetic field far from the surface of a neutron star is basically due to the star's own dipole field. Field lines which originate very close to the polar caps of a pulsar do not close within the light cylinder and go across it. These field lines are called open field lines. According to the model of Goldreich & Julian (1969) there is an electric field $E_1 = \mathbf{E{\cdot}B}/B$ parallel to the magnetic field B along these open lines. When charged particles move along these lines they get accelerated to very high energies. These accelerated charged particles emit γ-rays by curvature radiation and are subject to radiation reaction. It has been shown by Scharlemann *et al.* (1978) that radiation reaction is important when the period of the pulsar is given by the relation,

$$p < p_{rr} = 8{\cdot}108 (B_8 R_6)^{3/7} \text{ ms}. \tag{3}$$

The radiation reaction limited Lorentz factor for the electrons is given by (Scharlemann *et al.* 1978)

$$\gamma_e \sim \gamma_{rr} = 1.8 \times 10^6 r^{1/8} R_6^{6/8} p_{ms}^{-3/8} B_8^{1/4} \tag{4}$$

where p_{ms} is the period of rotation in millisecond, R_6 is the radius of the star in units of 10^6cm, B_8 is the star's magnetic field in units of 10^8 G and r is the distance from the star's surface to the point where the radiation is emitted. It has been assumed, while arriving at the above result, that most of the work done in accelerating the charged particles is converted into γ-emission due to curvature radiation. In passing we note that if the period of the pulsar is longer than that given by Equation (3), the energy of the electron is given by (Scharlemann *et al.* 1978)

$$\gamma_e \approx 6 \times 10^8 B_8 R_6^3 p_{ms}^{-5/2} [10^{-3} (r/R_6)^{1/2} - 1]. \tag{5}$$

Data regarding the periods and magnetic fields of the spun-up millisecond pulsars is rather scanty. Periods and magnetic fields of four millisecond pulsars in the galactic disc (Bhattacharya & Srinivasan 1991) and a few millisecond pulsars in globular clusters (Chen 1991) are known. From this limited data we can reasonably assume that the millisecond pulsars of this variety have a minimum period of about 1.6 ms, which is the value we have used in Equation (2). For a magnetic field of the order of 10^8 G and a star of radius 10_6cm, Equation (3) gives us the limiting value of the period below which the energy gained by an electron will be limited by radiation reaction. The limiting value of the period is $p \approx 10$ ms. This is also the order of the period which any rotating neutron star with initial rotation period of 1.6 ms would acquire as a result of its slow down during the age of the galaxy (Bhattacharya & Srinivasan 1991).

The curvature photons will escape the pulsar magnetosphere without any absorption enroute (Scharlemann *et al.* 1978). The typical energy of a curvature photon is (3/2) $hc\gamma_e^3 \backslash R_c$, where $R_C \approx (cr/\Omega)^{1/2}$ is the radius of curvature of the field lines at a distance r from the star's surface and Ω is the angular frequency of rotation of the pulsar. For periods between 1.6 ms and 10 ms and γ_e given by Equation (4), the photon energies lie in the range 5×10^3 MeV to 2×10^2 MeV. The curvature radiation power is given by,

$$l = (2/3)(e^2 c\gamma_e^4/R_c^2). \tag{6}$$

The $E_{||}$ field causes the charged particles to flow away from the stellar surface. The density of the charged particles coming out of the polar cap is according to Goldreich & Julian (1969),

$$n = \Omega B/2ce. \tag{7}$$

If $\Delta s \approx \pi\,(\Omega R/c)R^2$ denotes the area of the polar cap then the net rate at which the particles are emitted by the neutron star is

$$\dot{N} \approx \Delta snc = \Omega^2 BR^3/2ce. \tag{8}$$

The total power radiated at a distance r from the star's surface is $\approx I\dot{N}(r/c)$. Thus,

$$L(r) = e8\pi^3 BR^3\gamma_e^4/(3p^3c^2)\,\mathrm{erg\,s^{-1}}. \tag{9}$$

Using now the expression for γ_e from Equation (4) we get an expression for the luminosity at a distance r from the stellar surface as

$$L(r) = 4.2\times10^{31} B_8^2 R_6^6 p_{\mathrm{ms}}^{-9/2} r^{1/2}\,\mathrm{erg\,s^{-1}}. \tag{10}$$

Since r increases along the magnetic field lines, we assume that the dominant contribution to the total power comes from the vicinity of the light cylinder whose radius is given by $r \approx (c/\Omega)$. Since most of the curvature radiation is in the form of γ-rays, the luminosity $L(r)$ of a millisecond pulsar at the light cylinder can be written as L_γ and Equation (9) can be written as

$$L_\gamma = 9.2\times10^{34} B_8^2 R_6^6 p_{\mathrm{ms}}^{-4}\,\mathrm{erg\,s^{-1}}. \tag{11}$$

Since γ-emission forms a substantial fraction of the total spindown rate of a pulsar, we expect the γ-luminosity to be not much smaller than the spindown rate. This provides a reasonable basis for the present model. Equation (11) gives the γ-luminosity of individual millisecond pulsars. We now apply the above expression to find the luminosity of a globular cluster containing n_p millisecond pulsars. This is given by

$$L_\gamma^{gc} = \int F(p) L_\gamma n_p \mathrm{d}p. \tag{12}$$

Substituting Equation (11) and Equation (2) in Equation (12) we get

$$L_\gamma^{gc} = 9.1\times10^{34} n_p \int (\alpha-1) p_{\mathrm{min}}^{\alpha-1} p_{\mathrm{ms}}^{-\alpha} B_8^2 R_6^6 p_{\mathrm{ms}}^{-4}\mathrm{d}p. \tag{13}$$

The integration is to be performed with limits from p_{min} to p_{max}, that is, between 1.6 to 10 in our case. In view of Equation (1) and the data for millisecond pulsars given in Bhattacharya & Srinivasan (1991), it seems safe to assume that $p_{\mathrm{ms}} = kB_8^{6\backslash7}$ where k is of the order of unity. Substituting $p_{\mathrm{ms}} = B_8^{6\backslash7}$ in Equation (13) and integrating it, we arrive at the following result:

$$L_\gamma^{gc} = 3.8\times10^{36} n_{500}\,\mathrm{erg\,s^{-1}}, \tag{14}$$

where n_{500} is the number of millisecond pulsars in a globular cluster in units of five hundred. While carrying out the integration we have taken the stellar radius to be 10^6cm and in Equation (12), as is the practice, there should have been a beaming factor whose value varies between one and two. Here we have assumed it to be unity.

The assumption that $p_{ms} \propto B^{6\backslash 7}$ amounts to the expectation that during spindown the pulsar stays close to the spin-up line. Alternatively, following Chen (1991), we could assume that $p_{ms} \propto B$. In that case the luminosity of the globular cluster becomes

$$L_\gamma^{gc} = 2.9 \times 10^{36} n_{500} \,\mathrm{erg\,s^{-1}}, \quad (15)$$

which is not much different from the estimate of Equation (14). Therefore, it is reasonable to expect that on the basis of the present model the γ-luminosity of a globular cluster will be of the order of these estimates.

3. Discussion

It may be said that the millisecond pulsars in the globular clusters do not all have periods in the range 1.6 ms to 10 ms. However, the pulsars with periods in this range seem to be the most prolific emitters of γ-rays by the process discussed here. If the period of a pulsar is longer than that given by Equation (3) then the energy acquired by the electron after acceleration in the magnetosphere of the pulsar is given by Equation (5). To produce γ-rays with this energy by curvature radiation the magnetic field of the pulsar will have to be $> \sim 10^9$ G. If we assume this to be so, then its γ-luminosity can be shown to be proportional to $B_8^5\, P_{ms}^{-11}$. The rapid fall in luminosity with period of these pulsars makes them unimportant in comparison with the short period millisecond pulsars considered here. The globular clusters may also contain pulsars of the ordinary variety (which are not spun up). These may emit γ-rays by the Ruderman-Sutherland mechanism involving the polar gaps (Ruderman & Sutherland 1975). We have shown elsewhere (Bhatia, Chopra & Panchapakesan, 1987) that their γ-luminosity is much smaller than that given by the estimate in Equation (11). All in all, millisecond pulsars of periods between 1.6 ms and about 10 ms seem to be the dominant contributors to the γ-luminosity of globular clusters. There are indications (Manchester *et al.* 1991; Kulkarni 1990) that the globular clusters are very rich in millisecond pulsars, many of which are likely to have periods less than about 10 ms (all the eleven pulsars observed by Manchester *et al* (1991) have periods in this range). The case for the globular clusters as sources of γ-rays with estimated luminosities of the order of Equation (14) seems, therefore, well argued.

In addition to present calculation, there are two more models available in literature from which one could estimate γ-ray luminosity of a globular cluster which has. millisecond pulsars in it.

The first model is due to HTE (Harding, Tademaru & Esposito 1978). Though the model does not talk about pulsars having low magnetic fields (~10^8G) yet an extrapolation has been made from high (~ 10^{12} G) to low magnetic fields. With this extrapolation the THE model predicts a luminosity given by

$$L_\gamma^{gc}(\mathrm{HTE}) = 9.65 \times 10^{34} n_{500} \,\mathrm{erg\,s^{-1}}. \quad (16)$$

This luminosity is much less than what we have obtained from our calculation and makes the globular clusters rather faint γ-ray sources. The second model is by

CHR (Cheng, Ho & Ruderman 1986) as adapted by Chen (1991). This also involves the extrapolation from high to low magnetic fields. Their resulting luminosity is not much different from ours. It must, though, remain a moot point whether the models developed for high magnetic field pulsars can be applied to pulsars with low magnetic fields since some of the physical processes possible in one regime may not be possible in a different regime. Our calculations do not, however, suffer from any such conjecture.

Our results show that globular clusters containing millisecond pulsars may be bright sources of γ-rays. They are well within the reach of modern γ-ray detectors and we hope that greater effort would be made to detect these sources. Their detection would serve as a support for our ideas.

4. Conclusions

We have shown that if globular clusters contain a large number of resurrected neutron stars of millisecond periods, of which there is some evidence, then the collective emission of all the pulsars will make globular clusters sources of γ-rays. The estimated luminosities are such that these sources may be within the range of detection of the present-day instruments. We hope that the observers will make an effort to detect γ-rays from globular clusters and measure the luminosities of these sources. This data will, hopefully, help refine theories.

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