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SIGMA UPPER LIMITS TO THE HARD X-RAY/SOFT GAMMA-RAY EMISSION FROM THE MILLISECOND PULSARS OF THE NEARBY GLOBULAR CLUSTER 47 TUCANAE

D. Barret, P. Mandrou, M. Denis, and J. F. Olive
Centre d'Etude Spatiale des Rayonnements, 9 Avenue du colonel Roche, B. P. 4346, Toulouse Cedex, France
P. Laurent, A. Claret, F. Lebrun, and J. Paul
Service d'Astrophysique, Centre d'Etudes Nucléaires de Saclay, CEA, CEN Saclay, 91191 Gif-sur-Yvette Cedex, France
and
R. Sunyaev, E. Churazov, M. Gilfanov, A. Dyachkov, N. Khavenson,
B. Novikov, R. Kremnev, and A. Sukhanov
Space Research Institute, Profsojuznaya, ul. 84/32, 117296 Moscow, Russia
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ABSTRACT

We report upper limits to the hard X-ray/soft γ-ray emission from the millisecond pulsars (MSPs) of the nearby globular cluster 47 Tucanae. The observations have been performed by the French coded-mask imaging telescope SIGMA aboard the Soviet *GRANAT* spacecraft. From observations accumulated from 1990 April to 1992 May, the 2 σ upper limits to the 40–100, 100–300, 300–600, 600–900, and 900–1200 keV fluxes are 8.8×10^{-4}, 6.5×10^{-4}, 13.2×10^{-4}, 19.0×10^{-4}, and 22.4×10^{-4} photons cm^{-2} s^{-1}, respectively. These fluxes correspond to luminosities ranging from $\approx 2 \times 10^{35}$ ergs s^{-1} in the 40–100 keV band to $\approx 7.5 \times 10^{36}$ ergs s^{-1} in the band centered around 1 MeV.

The SIGMA results have been used to set upper limits on the magnetospheric efficiency (η) of the conversion of the MSP spin-down power into hard X-rays and soft γ-rays. These upper limits can be written: $\eta_{40-100\,\mathrm{keV}} \leq 2 \times 10^{-3} n_{100}^{-1} \langle L_{p,36} \rangle^{-1}$ and $\eta_{0.8-1.2\,\mathrm{MeV}} \leq 7.5 \times 10^{-2} n_{100}^{-1} \langle L_{p,36} \rangle^{-1}$ (n_{100} = number of MSPs in units of 100; $\langle L_{p,36} \rangle$ = average spin-down power in units of 10^{36} ergs s^{-1}).

The SIGMA upper limits are also compared with the high-energy fluxes predicted from theoretical models of the well-known ablating millisecond pulsar PSR 1957+20. This allows us to place upper limits on the number of objects similar to PSR 1957+20 in 47 Tuc. The limit numbers are too large to constrain the MSP population of the cluster.

On the other hand, stringent upper limits have been derived for the number of "hidden" MSPs (Tavani 1991). If, as predicted by the model, a large number of "hidden" MSPs actually does exist in 47 Tuc, then the SIGMA upper limits are not consistent with the hypothesis that they may be bright sources of hard X-rays and soft γ-rays.

Subject headings: globular clusters: individual (47 Tucanae, NGC 104) — pulsars: individual (PSR 1957+20) — gamma rays: observations

1. INTRODUCTION

In the standard scenario, millisecond pulsars (MSPs) are assumed to be the end product of low-mass X-ray binary systems, in which an old neutron star is spun up to a millisecond period during an accretion phase (cf. review by van den Heuvel 1987). Alternatively, some MSPs may result from the accretion-induced collapse of massive white dwarfs in binary systems (Grindlay & Bailyn 1988). In globular cluster cores, where the high stellar densities result in considerably higher formation rates of accreting binary systems, a large number of MSPs is expected. In the search for radio MSPs, 47 Tuc (NGC 104) quickly became a prime candidate, since not only does it have one of the densest cores, but, with a distance of only 4.1 kpc (Meylan 1988), it is also one of the closest.

The discovery of the first MSP, PSR 0021−72C (5.75 ms) in 47 Tuc, was reported by Manchester et al. (1990), using radio data recorded by the Parkes Radio Telescope. Further analysis of these data, together with new observations of 47 Tuc, accumulated up to 1991 February, led to the impressive discovery of 10 additional MSPs (Manchester et al. 1991). Two of the peculiarities of the 11 MSPs of 47 Tuc are that they all have periods less than 6 ms, and about half of them are in binary systems. The determination of the binary system parameters for two of them (e.g., PSR 0021−72J and PSR 0021−72E) indicates that the orbital period is short ($P_{\mathrm{orb}} = 0.12$ and 2.22 days, respectively), and that the mass of the companion is low (0.21 and 0.15 $M_{\odot}$, respectively; Manchester et al. 1991). In addition, PSR 0021−72J is eclipsed, indicating probably that its low-mass companion is being ablated, as in PSR 1957+20 (Fruchter et al. 1990) and in PSR 1744−24A in Terzan 5 (Lyne et al. 1990).

Stimulated by the previous discovery, suggesting the existence of a very large number of MSPs in 47 Tuc, several pointings devoted to the cluster were carried out in 1922 by the SIGMA telescope. We have combined these pointings with previous and later observations of the fields containing 47 Tuc but centered on the Small Magellanic Cloud X-ray sources (e.g., SMC X-1, SMC X-3). This paper reports on the complete set of the SIGMA observations of 47 Tuc accumulated from 1990 spring to 1992 spring.

2. OBSERVATIONS AND RESULTS

The SIGMA instrument is a French coded-mask imaging telescope operating in the 35–1300 keV range, launched in 1989

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TABLE 1

LOG LIST OF SIGMA OBSERVATIONS IN THE FIELD OF 47 TUCANAE

Observation Date	Exposure Time	Target Name	Sensitivity Factor
1990 Apr 5	113,137	SMC X-1	0.78
1991 Jan 25	62,970	SMC X-1	0.62
1991 Apr 21	67,341	SMC X-1	0.70
1992 Jan 7	67,089	47 Tuc	1.0
1992 Jan 8	61,713	47 Tuc	1.0
1992 Jan 9	38,466	47 Tuc	1.0
1992 Jan 15	61,091	SMC X-3	0.92
1992 May 17	68,220	SMC X-1	0.73
1992 May 18	56,200	SMC X-1	0.72

TABLE 2

2 σ UPPER LIMITS FOR THE HARD X-RAY/SOFT GAMMA-RAY EMISSION FROM 47 TUCANAE[a]

	ENERGY RANGE (keV)				
PARAMETER	40–100	100–300	300–600	600–900	900–1200
Photon flux[b]	8.8	6.5	13.2	19.0	22.4
Flux[c]	0.86	1.72	8.84	22.24	36.9
Luminosity[d]	0.175	0.35	1.8	4.5	7.48

[a] Derived from the sum of all the observations. A spectral index of 2 has been assumed for the source photon spectrum.

[b] $\times 10^{-4}$ photons s^{-1} cm^{-2}.

[c] $\times 10^{-10}$ ergs s^{-1} cm^{-2}.

[d] $\times 10^{36}$ ergs s^{-1} for an assumed distance of 4.1 kpc.

December aboard the Soviet *GRANAT* spacecraft. The basic features of SIGMA are described in detail in Paul et al. (1991). The SIGMA angular resolution ($\approx 15'$) does not allow resolution of 47 Tuc, whose core radius is $\approx 24''$. 47 Tuc was therefore imaged as a point source. The position of the point source was assumed to be at the core center. Its coordinates have been taken from Grindlay et al. (1984). Table 1 is the journal of the SIGMA observations performed in the fields containing 47 Tuc. It lists the observation date, the session duration corrected for the instrumental dead time, the primary target name, and the relative sensitivity in the direction of 47 Tuc ("sensitivity factor").

The analysis of the SIGMA observations has been made using the "spectral images" (SIs; Paul et al. 1991). These images have been corrected and deconvolved following standard procedures. Afterward, the SIs were summed over five energy bands (e.g., $\approx$40–100, 100–300, 300–600, 600–900, and 900–1200 keV). Finally, in each of the five images so obtained and for each session, we have searched for the flux observed in the pixel containing the core-center position of 47 Tuc.

No significant emission above the 2 σ confidence level has been recorded in any of the nine observations, in any of the five selected energy bands. Similarly, in the sum of the observations representing a total useful observing time of about 165 hr, no positive flux has been recorded from 47 Tuc. This sum has been used to compute the upper limits to the photon flux of 47 Tuc. An E^{-2} photon spectrum has been assumed for the source. The upper limits on that photon flux are given at the 2 σ confidence level and reported in Table 2 together with the corresponding hard X-ray/soft γ-ray fluxes as well as the luminosities assuming a distance of 4.1 kpc. Since they follow the SIGMA sensitivity curve (Paul et al. 1991), one may notice that these upper limits tend to increase above $\approx$300 keV.

3. DISCUSSION

Let us now compare the SIGMA upper limits to the primary radiation emitted by the MSPs themselves (§ 3.1), as well as to the secondary radiation expected at the shock interface between the pulsar wind and the surrounding matter, as in the case of PSR 1957+20 (§ 3.2), and in the case of the "hidden" MSPs (§ 3.3).

3.1. *Upper Limits to the Fraction of the MSP Spin-down Power Radiated in the SIGMA Energy Range*

Although MSPs represent a subject of intense theoretical work, no specific model for the radiation emitted by such objects exists so far. "Recycled" MSPs, being old neutron stars, are characterized by weaker surface magnetic fields B_s ($\approx 10^8$–10^9 G) and smaller rotation periods P (a few ms) in comparison with young canonical pulsars (such as the Crab or Vela pulsar). Despite these differences, it is often argued that the outer magnetosphere of a MSP may not differ too much from that of a young pulsar (Ruderman & Cheng 1988). This idea is based on the fact that the total magnetospheric voltage drop $\Delta V \approx 4\pi^2 P^{-2} B_s R^3 c^{-2}$ and the magnetic field at the light cylinder are comparable for these two classes of pulsars (Ruderman & Cheng 1988; Chen 1991). The outer magnetosphere of the young pulsars is thought to be the seat of production of a strong 10^{12} eV $e^{\pm}$ wind as well as of the observed X-ray and γ-ray radiations (Cheng, Ho, & Ruderman 1986).

Assuming that the mechanisms involved in the high-energy emission of young pulsars work also at millisecond periods and low magnetic field strengths, then MSPs have to be considered as potential sources of high-energy emission. In particular, with this assumption, it is predicted in the well-known "outer gap model," that MSPs may be sources of high-energy emission from γ-rays down to $\approx$100 keV (Ruderman & Cheng 1988). However, so far no MSP has been detected at high energies, and therefore neither the emission spectrum nor the amount of energy radiated by a MSP is known, the lack of positive detection indicating simply that only a modest part of the MSP spin-down power is converted into high-energy photons. This makes clearly relevant the search for high-energy emission from globular clusters, where the detection probability of such a radiation is strongly enhanced by the existence of a large number of MSPs. To date, this is the best way to test the hypothesis that MSPs are sources of high-energy emission. If this turns out to be the case, then the observations should allow us to make comparisons between the emission properties of MSPs and those of younger pulsars (see, for example, Chen 1991 for a comparison between MSPs and Vela-type pulsars).

In the hard X-ray/soft γ-ray domain, some valuable information can be gained from the SIGMA observations. The fact that 47 Tuc has not been detected allows one to put an upper limit on the fraction of the MSP spin-down power radiated in the SIGMA energy range. Since the distribution of the number of MSPs with respect to their spin-down power is not yet determined, in the simplest way we assume that they all have the same spin-down power: an average value defined as $\langle L_{p,36} \rangle$ in units of 10^{36} ergs s^{-1}. The number of MSPs (n_{100}) is defined in units of 100. With these definitions, the SIGMA upper limits on the efficiency of conversion (η) are given as follows: $\eta_{40-100\,\mathrm{keV}} \leq 2 \times 10^{-3} n_{100}^{-1} \langle L_{p,36} \rangle^{-1}$ in hard X rays

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(40–100 keV), and $\eta_{0.8-1.2\,\mathrm{MeV}} \leq 7.5 \times 10^{-2} n_{100}^{-1} \langle L_{p,36} \rangle^{-1}$ around 1 MeV (0.8–1.2 MeV). For comparison, for the Crab pulsar, in the same energy bands, the magnetospheric conversion efficiencies are known to be of the order of 10^{-3} and 5×10^{-4}, respectively. Therefore, with the previous upper limits, future estimates of n_{100} and $\langle L_{p,36} \rangle$ will make possible a direct comparison between the magnetospheric efficiencies of MSPs and young pulsars.

3.2. *Upper Limits to the Number of Ablating MSPs like PSR 1957+20*

The process of the ablation of a very low mass companion by the energetic radiation produced by a MSP was anticipated by Ruderman, Shaham, & Tavani (1989). Strong support for the existence of this process was provided not long after by the discovery of the eclipsing MSP PSR 1957+20, whose companion appears to be ablating (Fruchter et al. 1990). Following this discovery, several theoretical papers specific to PSR 1957+20 proposed mechanisms able to drive a wind from a low-mass companion (Kluzniak et al. 1988; Phinney et al. 1988; Tavani 1989; Cheng 1989; Krolik & Sincell 1990; Arons & Tavani 1993). All of these models assume that most of the MSP spin-down power is carried off in the form of a relativistic wind of electron/positron pairs. If a substantial part of this relativistic wind is converted into X-rays and soft γ-rays, then absorption of these photons in the outer atmosphere of the irradiated star would be very effective in driving an evaporative wind (Tavani 1989).

The conversion of TeV $e^{\pm}$ particle energy into photons through synchrotron radiation or inverse Compton scattering on background cool photons may occur at the shock interface between the pulsar wind and the mass outflow from the companion of PSR 1957+20 (Kluzniak et al. 1988; Phinney et al. 1988). Kluzniak et al. (1988) (hereafter "model I") estimated that for a pulsar having a spin-down power of about 10^{36} ergs s^{-1}, the synchrotron radiation of the TeV $e^{\pm}$ pairs in the ≈ 100 G companion's magnetic field irregularities would have a luminosity of the order of 10^{33} ergs s^{-1} in the MeV region. For PSR 1957+20, whose spin-down power is $\approx 1.2 \times 10^{35}$ ergs s^{-1}, the MeV luminosity would be $\approx 10^{32}$ ergs s^{-1}. Phinney et al. (1988) (hereafter "model II") predicted that the cooling of the pairs at the shock would give rise at Earth to flux in the X-ray band of $1.6 \times 10^{-11} f_x$ ergs cm^{-2} s^{-1}, and an intensity at ≈ 1 MeV of $1.6 \times 10^{-5} f_\gamma$ photons cm^{-2} s^{-1}, considering that the pulsar timing age of PSR 1957+20 is $\tau \approx 2 \times 10^9$ yr. The factors f_x and f_γ are dimensionless parameters representing the fraction of the energy liberated in the shocked-pulsar wind, respectively in the X-ray and the MeV band. Taking 1.5 kpc for the distance of PSR 1957+20 and scaling them to the distance of 47 Tuc (4.1 kpc), the fluxes predicted in the second model have still to be divided by a factor of about 7. Since all the fluxes listed above are below the sensitivity threshold of SIGMA, we will convert the SIGMA upper limits into limits to the number of PSR 1957+20–like MSPs in 47 Tuc.

For model I, from the upper limit derived between 900 and 1200 keV ($F_{900-1200\,\mathrm{keV}} \leq 2.2 \times 10^{-3}$ photons cm^{-2} s^{-1}, $L_{900-1200\,\mathrm{keV}} \leq 7.5 \times 10^{36}$ ergs s^{-1}), the number of MSPs similar to PSR 1957+20 has to be less than $\approx 7.5 \times 10^4$, and less than $\approx 1000 f_\gamma^{-1}$ in model II. Given a better sensitivity of SIGMA in the hard X-ray range, from the upper limit derived between 35 and 100 keV ($f_{35-100\,\mathrm{keV}} \leq 8.6 \times 10^{-11}$ ergs s^{-1} cm^{-2}), we obtain for model II a number limit of $\approx 40 f_x^{-1}$ assuming that the energy is radiated in the specified energy band.

Based on recent work on the structure and particle acceleration in relativistic collisionless shocks applied to the Crab Nebula emission (Hoshino et al. 1992), Arons & Tavani (1993) computed in more detail both the emission arising at the relativistic shock produced by the pulsar wind in the nebula (Kulkarni & Hester 1988) and that emitted at the shock constraining the mass outflow from the companion. A soft component 10^{-2} eV to 40 keV is produced in the nebula, whereas a harder one arises within the binary and is emitted in the range from X-rays to MeV γ-rays. For the canonical parameters adopted in their model (Arons & Tavani 1993), we derive limit numbers of PSR 1957+20–like MSPs in 47 Tuc of the order of 10^3, depending on the energy band considered.

As stressed in Arons & Tavani (1993), the emission process and by inference the fluxes produced are strongly dependent on both the wind and shock properties and the binary system parameters. Therefore, the SIGMA upper limits, which are obviously too large to constrain the MSP population of 47 Tuc have to be considered as only indicative. It appears clearly, however, that the detection of the shock emission from ablating systems in the SIGMA energy range requires a sensitivity improvement of the future experiments by at least one order of magnitude.

3.3. *Upper Limits to the Number of "Hidden" MSPs*

Following Tavani (1991), the two most extensively studied ablating MSPs (i.e., PSR 1957+20 and PSR 1744−24A) have sufficiently different eclipsing properties to define two distinct classes of ablating MSPs. The first class is represented by PSR 1957+20 and contains ablating MSPs characterized by well-defined and periodic eclipses. The prototype of the second class is PSR 1744−24A, which shows more erratic and sometimes intermittent radio eclipses (Lyne et al. 1990; Nice et al. 1990). In addition to these two classes of MSPs, Tavani (1991) demonstrated that a third class can be expected from theoretical computations of the dynamic properties of these systems, the so-called "hidden" MSPs. These MSPs would be completely enshrouded in the evaporated material escaping from the companion. They would be "hidden" because their radio emission would be absorbed in the surrounding "bubble." At the interface between the pulsar wind and the inner parts of this "bubble," shock mechanisms similar to that invoked in ablating models (Arons & Tavani 1993) would be involved, but the resulting fluxes would be higher, given a larger surface of the evaporated material exposed to the pulsar wind (Tavani 1991). The resulting spectrum would be either a power law (photon index ≈ 2) extending from a few keV to GeV energies (case I) or a spectrum peaked at low energies (in the soft X-ray range; case II), depending on the wind and shock properties (Tavani 1991). In the first case, which is of interest for us, the predicted hard X-ray/soft γ-ray flux from a single "hidden" MSP is given as follows:

$$F(E > 35\,\mathrm{keV}) \sim 8 \times 10^{-3} \times \frac{\langle L_{p,36} \rangle}{d_{\mathrm{kpc}}^2} \frac{\varepsilon}{0.2} f_{\mathrm{SIGMA}} \text{ photons cm}^{-2}\,\text{s}^{-1},$$

where $\langle L_{p,36} \rangle$ is defined as above; d_{kpc} is the distance in kiloparsecs; ε is a dimensionless parameter normalized to the value derived for the Crab pulsar, giving the conversion efficiency of the pulsar wind energy into radiation (Hoshino et al. 1992);

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and f_{SIGMA} defines the fraction of the shock emission which goes into the SIGMA energy band. Therefore, to be detectable by SIGMA, a "hidden" MSP should satisfy the condition

$$(\langle L_{p,36}\rangle/d_{\mathrm{kpc}}^2)f_{\mathrm{SIGMA}} \approx 2$$

(Tavani 1992). Normalized to the distance of 47 Tuc (4.1 kpc; Meylan 1988), the SIGMA upper limits (40–100 keV) can then be rewritten in terms of upper limits on the number of "hidden" MSPs (N_{hmsp}) as follows:

$$N_{\mathrm{hmsp}} \leq 2\langle L_{p,36}\rangle^{-1} f_{\mathrm{SIGMA}}^{-1} \,.$$

The low upper limit derived above clearly deserves some comments, since in 47 Tuc, many "hidden" MSP candidates have been proposed (Tavani 1991), as, for example, some of the 20 "blue stragglers" recently discovered in the cluster core (Paresce et al. 1991) as well as the puzzling MSP PSR 0021−72A (Ables 1989; Manchester et al. 1991). In this context, if the prediction that 47 Tuc contains a large population of "hidden" MSPs is indeed correct, then the SIGMA results become inconsistent with the first prediction that they may be bright sources of hard X-rays/soft γ-rays. This means that for case I of the model f_{SIGMA} has to be small. This may indicate that the energy is radiated outside the SIGMA range either (i) above, in the γ-ray domain with the spectrum characterized by a spectral break or a cutoff toward the hard X-ray energies, or (ii) below, in the classical X-ray range (case II). However, the latter possibility seems difficult to reconcile with previous soft X-ray observations of 47 Tuc performed by the HRI and IPC instruments aboard the *Einstein Observatory* (Hertz & Grindlay 1983). Indeed, these observations have demonstrated that 47 Tuc contains only one weak and moreover variable soft X-ray source, 1E 0021.8−7221, which is thought to be a cataclysmic variable (Paresce, De Marchi, & Ferraro 1992; Aurière et al. 1989; Hertz & Grindlay 1983). As far as the hypothesis that "hidden" MSPs may be sources of γ-rays, it could be easily tested with globular cluster observations performed by the *Compton Gamma Ray Observatory* experiments EGRET and COMPTEL, whose sensitivities, especially for EGRET, are expected to be good enough to detect such an emission even from a single high-luminosity "hidden" MSP (Tavani 1992).

4. CONCLUSIONS

The SIGMA observations of 47 Tuc reported here represent the first attempt to search for hard X-ray/soft γ-ray emission from a globular cluster known to contain a large number of millisecond pulsars. If, as suggested by the 47 Tuc data, the collective radiation of these millisecond pulsars is not detectable by SIGMA, our next task will be clearly to improve our upper limits. This could be achieved for the closest globular clusters located in the direction of the Galactic center, for which a very long exposure time has already been accumulated by SIGMA. Establishing better upper limits will be very valuable in constraining the number of cluster pulsars as well as the models of their formation and emission.

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