

# HESS upper limit on the very high energy $\gamma$ -ray emission from the globular cluster 47 Tucanae (Research Note)

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## ABSTRACT

Observations of the globular cluster 47 Tucanae (NGC 104), which contains at least 23 ms pulsars, were performed with the HESS telescope system. The observations lead to an upper limit of  $F(E > 800 \text{ GeV}) < 6.7 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$  on the integral  $\gamma$ -ray photon flux from 47 Tucanae. Considering millisecond pulsars as the unique potential source of  $\gamma$ -rays in the globular cluster, constraints based on emission models are derived: on the magnetic field in the average pulsar nebula and on the conversion efficiency of spin-down power to  $\gamma$ -ray photons or to relativistic leptons.

**Key words.** Galaxy: globular clusters: individual: 47 Tucanae – stars: pulsars: general – gamma rays: observations

## 1. Introduction

Millisecond pulsars (msPSRs) are usually categorized among the radio pulsar population by limits on their spin period ( $P \leq 50 \text{ ms}$ ) and, when available, intrinsic spin-down rate ( $\dot{P}_{\text{int}} \leq 10^{-18} \text{ s s}^{-1}$ ). They are old neutron stars, possibly re-accelerated by interactions with a companion, as first proposed in Alpar et al. (1982). Very high energy (VHE) emission from this type of object has been predicted via various radiation mechanisms. For individual objects, Inverse Compton (IC) or Curvature Radiation (CR) emission due to the acceleration of leptons above the polar cap (Harding et al. 2005; Bulik et al. 2000) have been proposed. For binary systems, an additional possibility would be the interaction between pulsar wind driven outflows and the stellar wind

of the companion (see for instance Dubus 2006). The spin-down power, typically lower than  $10^{35} \text{ erg s}^{-1}$ , entails expected individual  $\gamma$ -ray fluxes well below the detection threshold of current instruments.

However, groups of msPSRs have been identified in Galactic globular clusters (see e.g. Manchester et al. 1991), allowing for larger fluxes from an ensemble of unresolved sources. Out of more than 185 pulsars with  $P \leq 50 \text{ ms}$  known in the year 2008<sup>1</sup> (Manchester et al. 2005), 131 belong to globular clusters<sup>2</sup>. Globular clusters (GCs) are old high-density galactic structures, with ages close to the age of the Galaxy itself (see for instance

<sup>1</sup> <http://www.atnf.csiro.au/research/pulsar/psrcat/> [v1.34].

<sup>2</sup> <http://www2.naic.edu/~pfreire/GCpsr.html> [on 2008 August 7].

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Gratton et al. 2003). Their age indeed suggests evolved embedded stellar populations including compact (binary) objects, which are considered potential progenitors to msPSRs, as discussed e.g. in Benaquista (2006). The GCs Terzan 5, 47 Tucanae and M 28, in this order, host the largest identified msPSR populations (Ransom 2008).

47 Tucanae (NGC 104) is one of the largest Galactic GCs known to date, with an estimated mass of  $10^6 M_{\odot}$  and an age of  $11.2 \pm 1.1$  Gyr (Gratton et al. 2003). Optical observations by the Hubble Space Telescope, described in McLaughlin et al. (2006), allowed precise measurements of its location, centered at  $\alpha_{2000} = 0^{\text{h}}24^{\text{m}}05^{\text{s}}.67$  and  $\delta_{2000} = -72^{\circ}04'52''.62$  and placed it at a distance of  $4.0 \pm 0.35$  kpc. The surface brightness distribution allows the estimation of a core radius of  $r_0 = 20'.84 \pm 5'.05$ , a half-mass radius  $r_h \approx 2.6'$  and a tidal radius  $r_t \approx 0.6''$ , using the model of King (1966). In 47 Tucanae, 23 pulsars so far were revealed, with radio observations predominantly using the Parkes telescope (Freire et al. 2003), with periods in the range 2–8 ms, averaging at 4 ms, all located within  $1.2'$  of the centre of the GC. Based on the unresolved 20 cm radio flux from the core of 47 Tucanae, McConnell et al. (2004) estimated that up to 30 pulsars could be radio-detected. A study of the dispersion measure of the observed pulsar period derivatives (Freire et al. 2001) provided an estimation of the average msPSR intrinsic period derivative with  $\langle \dot{P}/P \rangle_{\text{int}} \approx 10^{-18} \text{ s}^{-1}$  and hence a surface dipole magnetic field  $B_s \approx 2.6 \times 10^8$  G and a spin-down power of  $L_{\text{sd}} \approx 10^{34} \text{ erg s}^{-1}$ .

At higher energies, Heinke et al. (2005) reported, from Chandra X-ray observatory data on 47 Tucanae, some 200 X-ray point sources, which belong to several object classes including cataclysmic variables, low-mass X-ray binaries (XRB), and the radio-detected msPSRs. They derive, from a tentative identification of the unknown sources they detected, an upper limit on the number of pulsars in the core of 47 Tucanae of about 60, assuming individual fluxes similar to the X-ray detected ones. Roughly two thirds of these msPSRs have a stellar companion ( $M \leq 0.2 M_{\odot}$ ). The X-ray spectrum of a msPSR in a GC can be described by a thermal component plus single power law, with typical X-ray (0.5–6 keV) fluxes around  $10^{31} \text{ erg s}^{-1}$  (Bogdanov et al. 2006). A few msPSRs exhibit X-ray pulsations, although with pulsed fractions below 50% for most of them (Cameron et al. 2007). The presence in 47 Tucanae of “hidden” msPSRs, detectable in hard X-rays but not in radio, has been excluded, within the uncertainty of the model by Tavani (1991), by the high-energy X-ray (0.75 to 30 MeV) upper limits reported by COMPTEL (O’Flaherty et al. 1995). From EGRET observations, Michelson et al. (1994) produced a photon flux upper limit of  $5 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$  above 100 MeV at 95% confidence level. In the same energy band, a detection of 47 Tucanae was just announced with the release of the FGST bright source list<sup>3</sup>, see Abdo et al. (2009), slightly below the EGRET upper limit by Michelson et al. (1994). These are discussed in Sect. 3.

In the TeV range, previous observations of globular clusters resulted in upper limits. A limit on the steady photon flux from M 13 (5 msPSRs, 7 kpc) was established by the Whipple Telescope (Hall et al. 2003) at  $1.08 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$  above 500 GeV. 47 Tucanae was observed by the Durham Mark III telescopes, with a resulting upper limit on the photon flux in pulsed emission from selected pulsars of  $4.4 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$ , above a threshold of 450 GeV (Bowden et al. 1991). Periodic VHE emission from an XRB in 47 Tucanae above 5 TeV was

reported once, by de Jager et al. (1989) during a remarkably high X-ray flux episode (Auriere et al. 1989). Such event has not been reported since then in 47 Tucanae.

The large number of identified msPSRs in 47 Tucanae and the compactness of the msPSR population at relatively close distance motivated HESS observations of this GC, to investigate the predicted VHE emission from this class of objects. The results of these observations are presented in Sect. 2. Given the unknowns regarding VHE-emitting XRB, the interpretation given in Sect. 3 centers on a collective signature from the msPSR population at TeV energies.

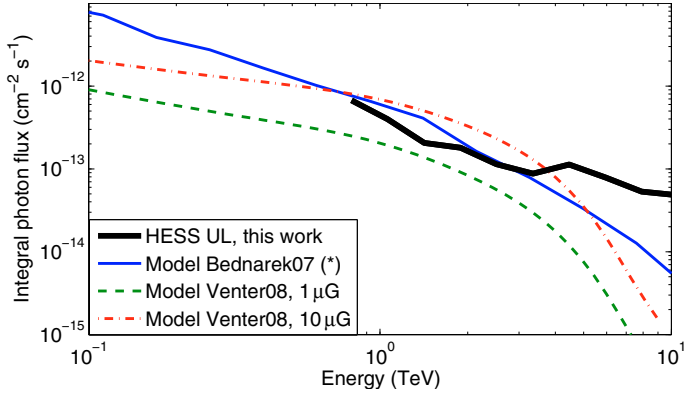
## 2. Observations and analysis

HESS is an array of four Imaging Atmospheric Cherenkov Telescopes, located in the Khomas Highland of Namibia. Stereoscopic analysis methods allow efficient background (cosmic ray) rejection and accurate energy and arrival direction reconstruction for  $\gamma$ -rays in the range 100 GeV–100 TeV. For point-like sources, the system has a detection sensitivity of 1% of the flux level of the Crab Nebula above 1 TeV with a significance of  $5\sigma$  in 25 h of observation. A thorough discussion of the HESS standard analysis and performance of the instrument can be found in Aharonian et al. (2006a).

A total of 13 h of 4-telescope data have been taken by HESS between October and November 2005 on 47 Tucanae (excluding data taken during bad weather or affected by hardware irregularities). The target was observed with an average zenith angle of  $50^{\circ}$  and mean target offset of  $1^{\circ}$  from the centre of the field of view. Applying the HESS analysis “standard” cuts for point-like sources (see Aharonian et al. 2006a), the energy threshold is about 800 GeV and the point-spread function above 1 TeV is  $0.11^{\circ}$ , too large to resolve the core of 47 Tucanae. Tighter cuts would slightly improve the sensitivity and angular resolution but also increase the energy threshold, further reducing the chances of a detection according to the models (see Sect. 3). Several methods for  $\gamma$ -ray reconstruction (the Hillas parameters method and a semi-analytical approach described in Rolland et al. 2004) and background estimation (the “ring” and “reflected” algorithms discussed in Aharonian et al. 2006a) were used, with consistent results.

We find no significant  $\gamma$ -ray event excess over the estimated background from the direction of 47 Tucanae. With standard cuts and using the “reflected” background estimation method, the significance of the excess in the  $0.11^{\circ}$  radius integration area is  $0.7\sigma$ . This allows us to set an upper limit on the flux from the target region. We determined upper limits according to Feldman & Cousins (1998) with a 99% confidence level, assuming a point-like source and a power law photon flux energy spectrum of index  $\alpha = 2$ . The integral flux upper limit discussed here and shown in Fig. 1 was derived using the standard Hillas analysis, consistent within 20% with cross-check analyses. Increasing the photon index to  $\alpha = 3$  does not modify the result by more than 20%. The upper limit on the integral photon flux in the HESS energy range for this data set (800 GeV–48.6 TeV, from the energy range of the collected events) is  $6.7 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$  or  $\sim 2\%$  of the Crab flux. This translates into a limit on the energy flux in the same energy range of  $6.8 \times 10^{33} \text{ erg s}^{-1}$  when placing 47 Tucanae at 4 kpc distance. We also investigated an extended region ( $0.2^{\circ}$  radius), without finding a significant excess. We do not discuss the extended case further due to the compact distribution of the msPSRs in 47 Tucanae and the generally weaker limits derived for extended regions.

<sup>3</sup> [http://fermi.gsfc.nasa.gov/ssc/data/access/lat/bright\\_src\\_list/](http://fermi.gsfc.nasa.gov/ssc/data/access/lat/bright_src_list/)



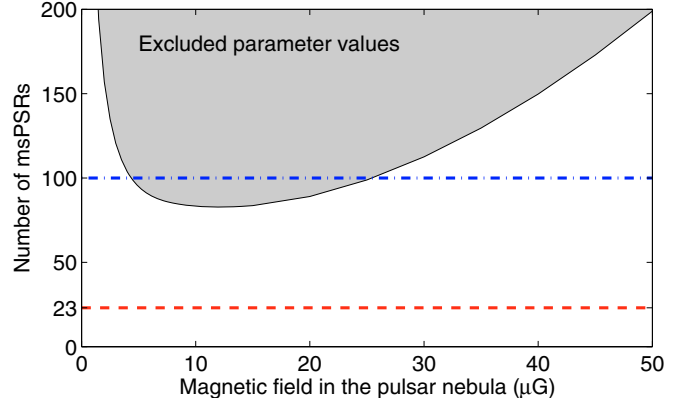
**Fig. 1.** Upper limit integral flux curve derived from the HESS observations of 47 Tucanae (assuming a photon index of  $\alpha = 2$ ), for “standard” cuts, at the 99% confidence level. Predicted fluxes for 100 msPSRs were added for comparison, rescaled for a distance of 4 kpc. (\*) Curve adapted from [Bednarek & Sitarek \(2007\)](#), for  $\epsilon_e = 0.01$ ,  $E_{\min} = 100$  GeV and  $\alpha = 2$ , rescaled to  $L_{\text{sd}} = 10^{34}$  erg s $^{-1}$  (see Sect. 3 for details).

### 3. Discussion

The HESS upper limit on the  $\gamma$ -ray flux emitted by 47 Tucanae can be confronted with scenarios of VHE  $\gamma$ -ray emission by msPSRs involving accelerated leptons in progressively larger regions: close to the pulsar, inside the pulsar wind nebula (PWN), at the boundary of the eventual PWN, or further away in the GC where pulsar winds may interact. The comparison to PWNs detected in the VHE range is also discussed. We only consider here average properties of the msPSRs in 47 Tucanae, as summarized in Sect. 1, for populations of 23 (detected) or 100 sources. While observational results favor smaller numbers, results from dynamical models of GCs, e.g. from [Ivanova et al. \(2008\)](#), suggest possibly larger populations. Unless stated otherwise, the following constraints scale linearly with the number of pulsars.

The production of  $\gamma$ -rays in the pulsar magnetosphere has been proposed in (at least) two different general scenarios, which consider different production sites: the “outer gap” or the “polar cap”. In the “outer gap” model (see e.g. [Chen & Ruderman 1993](#)), low values of the surface magnetic field (estimated from the spin-down rate) and pulsar period, which define the conditions near the light cylinder, are believed to generally prevent VHE emission from msPSRs. Although the “polar cap” model (discussed for instance in [Harding et al. 2005](#)) does not have such restriction on the conditions for VHE emission, both classes of model predict the flux to drop off sharply between 1 and 100 GeV, as discussed for a single msPSR in [Chiang & Romani \(1992\)](#) and in [Wang et al. \(2005\)](#) for a large population. The upper limit by EGRET ([Michelson et al. 1994](#)) does constrain some of these models. Pulsed emission is also predicted, e.g. in [Venter & de Jager \(2008\)](#) for 47 Tucanae, to drop before 100 GeV, below the limit by [Bowden et al. \(1991\)](#). The Fermi detection will undoubtedly renew the discussion on these processes, but interpretation in the 20 MeV–300 GeV band will be challenging, between potentially pulsed emission from one or more msPSR, confused or unresolved sources, and the overall steady emission component, which could be tied to scenarios also valid at energies above our quoted threshold.

The IC component, produced either in the magnetosphere or further away from the compact object, does extend to the energies considered here, but in most cases with only very low fluxes ([Bulik et al. 2000](#)). Still, when considering populations



**Fig. 2.** Upper limit on the number of msPSRs in 47 Tucanae for a given average magnetic field in the pulsar nebula, using the model by [Venter et al. \(2009\)](#) and the HESS flux upper limit. The dashed lines indicate the number of observed msPSRs (23) and the 100 msPSRs hypothesis discussed here.

of sources, as done in [Venter et al. \(2009\)](#), IC emission from the pulsar nebulae might reach observable levels. Their Monte Carlo simulations of msPSR populations, accounting for the observed range of parameters ( $P$ ,  $\dot{P}_{\text{int}}$ , viewing geometry), predict the cumulative flux from 100 msPSRs, as illustrated in Fig. 1. The efficiency of the IC emission in the pulsar nebula increases with the strength of the nebular magnetic field  $B$  (in relation with the increased confinement time) until losses by synchrotron radiation become dominant. For a given value of  $B$ , the HESS upper limit can be normalized by the predicted flux per pulsar to obtain the maximum allowed number of msPSRs, as done in Fig. 2. Large msPSR populations are thus excluded, down to 80 objects for  $B = 12$   $\mu\text{G}$ . In this model, the prediction falls short of providing constraints for only 23 msPSRs. Using the limit on the magnetic field strength in the nebula – post-shock – of the millisecond PSR J0437-4715 by [Zavlin et al. \(2002\)](#) of  $B < 18$   $\mu\text{G}$  and possibly lower (see the discussion in that reference), and assuming similar properties for 100 msPSRs, this would suggest  $B \leq 5$   $\mu\text{G}$  in the average pulsar nebula.

Another scenario for producing VHE  $\gamma$ -ray emission relies on particle acceleration at the shock discontinuity of a PWN. Thorough discussions on pulsar winds can be found in [Kaspi et al. \(2006\)](#). In X-rays, pulsar wind emission from msPSRs has been observed, in the so-called “black widow” discussed in [Stappers et al. \(2003\)](#), with luminosities similar to those of canonical pulsars, but not in a GC. In this object, as well as for the “Mouse” pulsar ([Gaensler et al. 2004](#)), there are indications of interaction with the interstellar medium, suggesting a bow shock geometry primarily driven by the proper motion of the pulsar rather than by its accelerated particles. However, [Cheng et al. \(2006\)](#) established that in a GC such bow shock emission would be hampered by the geometry and stellar density. VHE  $\gamma$ -ray emission from several PWNs has already been detected and [Cheng et al. \(1986\)](#) suggested that msPSRs host the same leptonic emission processes as young pulsars like Vela X (290 pc,  $L_{\text{sd}} \approx 10^{36}$  erg s $^{-1}$ ). Without assuming a particular emission process (see [Horns et al. 2006](#), for a hadronic VHE emission model for the Vela X PWN), we derive the flux expected if similar objects were located in 47 Tucanae. The VHE detection of the Vela X PWN ([Aharonian et al. 2006b](#)) gives an integral photon flux  $F(E > 800$  GeV)  $\approx 1.5 \times 10^{-11}$  cm $^{-2}$  s $^{-1}$ . Scaling for the distance and spin-down power of the pulsar associated with the Vela X nebula to the pulsars in 47 Tucanae amounts to a

**Table 1.** Upper limits on conversion efficiencies from spin-down power.

Model ( $\ddagger$ ) [ $E_{\min}$ (GeV), $\alpha$ ]				Measured $\langle L_{\text{sd}} \rangle$
100, 2.1	100, 3.0	1, 2.1	1, 3.0	
$\epsilon_e$				$\epsilon_{\text{sd}}^{1-10}$
0.003	0.01	0.01	0.6	0.007

factor  $5.3 \times 10^{-5}$ . We cannot constrain this model, as 840 “Vela-like” msPSRs would be required to reach our flux upper limit. From pulsar properties and measured fluxes, it is usual to estimate the fraction of the spin-down power converted to  $\gamma$ -rays,  $\epsilon_{\text{sd}}$ , as compiled recently in [Hessels et al. \(2008\)](#) for the VHE-detected PWNs in the 1–10 TeV energy band. For 47 Tucanae, this fraction is limited by  $N_p \times \epsilon_{\text{sd}}^{1-10} \leq 0.7$ . Any msPSR population with  $N_p \geq 23$  gives  $\epsilon_{\text{sd}}^{1-10}$  in the broad range of detected PWNs ( $8 \times 10^{-5}$  to 0.05). From this point of view, the msPSRs in 47 Tucanae cannot be distinguished from the much younger and more energetic pulsars detected through the VHE emission of their PWN. Detailed studies of the specificities of each PWN might clarify the picture.

Nonetheless, a scenario by [Bednarek & Sitarek \(2007\)](#) proposes that the energy of primary particles for the IC process increases through the interaction of the leptonic pulsar winds inside the GC. No observational evidence for such wind-wind interaction has yet been found. They predict appreciable VHE  $\gamma$ -ray fluxes for a population of 100 msPSRs when the power emitted by each pulsar is fixed at  $1.2 \times 10^{35} \text{ erg s}^{-1}$ . The distribution in energy of the leptons produced by a pulsar is assumed to follow a power law of index  $\alpha$ , above a minimum energy  $E_{\min}$ . In most cases, the predicted flux in the HESS energy range for 47 Tucanae should be above the detection threshold of the instrument. According to this model, a non-detection translates in a limit on  $N_p \times \epsilon_e$ , the number of pulsars times the conversion efficiency from the pulsar spin-down power into relativistic electron-positron pairs (and not  $\epsilon_{\text{sd}}$ , from spin-down to photons). The available HESS data on 47 Tucanae do not allow to reach the reference sensitivity used by [Bednarek & Sitarek \(2007\)](#), estimated (for 50 h of observation at  $20^\circ$  zenith angle and  $0.5^\circ$  offset) as a photon flux of about  $2.0 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$  above 800 GeV, a factor  $f_{\text{sens}} \approx 3.35$  lower than the result presented here. Besides, the values assumed in [Bednarek & Sitarek \(2007\)](#) for the distance to 47 Tucanae (4.5 kpc) and the individual spin-down power ( $1.2 \times 10^{35} \text{ erg s}^{-1}$ ) may be too large. Overall, a factor  $f_{\text{sens}} \times (L_{\text{sd}}^{\text{Bednarek07}}/L_{\text{sd}}^{\text{data}}) \times (d^{\text{data}}/d^{\text{Bednarek07}})^2 \approx 31.8$  must be applied when comparing their model predictions to the presented HESS upper limit. Since their original limit is on  $N_p \times \epsilon_e$ , a linear rescaling can be applied when changing the number of pulsars. Rescaled conversion efficiencies, derived from the HESS upper limit above 800 GeV assuming 100 msPSRs, are given in Table 1 for their model (noted  $\ddagger$ ) and for the conversion from spin-down power to VHE emission ( $\epsilon_{\text{sd}}^{1-10}$ ) discussed above. The comparison depends on the injection spectrum of the leptons produced by the pulsars. All the proposed scenarios are constrained ( $\epsilon_e < 1$ ) in the 100 msPSRs case, with most limits on the efficiency clearly below the estimated  $\epsilon_e \approx 0.1$  for the Crab nebula ([Bednarek & Sitarek 2007](#)), even when assuming only 23 msPSRs. The exception is the scenario where most of the leptons are produced with low energy ( $E_{\min} = 1 \text{ GeV}$  and  $\alpha = 3$ ): the constraints weaken to  $\epsilon_e \leq 0.6$  for 100 msPSR and  $\epsilon_e \geq 1$  (no constraint at all) for 23 msPSRs.

## 4. Conclusions

The upper limit of the VHE  $\gamma$ -ray photon flux obtained from HESS observations of 47 Tucanae,  $F(E > 800 \text{ GeV}) < 6.7 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$ , is at present the second limit for a GC with a sizable population of msPSRs. Given the size of this population, it is the most constraining upper limit on the flux from an ensemble of msPSRs so far derived.

Comparing this result to emission models, we considered msPSRs as the only potential  $\gamma$ -ray sources in the GC. Owing to the high energy threshold of these observations, emission models for the pulsar polar region, generally predicting low fluxes at these energies, cannot be constrained, except when assuming msPSR populations much larger than considered here (23–100). These numbers, according to [Venter et al. \(2009\)](#), may however be sufficient for the total IC emission to reach flux levels where the number of pulsars can be limited, depending on the strength of the magnetic field in the pulsar nebula, down to  $B \leq 5 \mu\text{G}$  in the average pulsar nebula for 100 msPSRs. The limit on the conversion efficiency from spin-down power to VHE flux (see Table 1) is compatible with the results available for VHE-detected PWNs. Collective IC emission as proposed by [Bednarek & Sitarek \(2007\)](#) cannot be more efficient than in the Crab nebula for most of their sets of parameters. Complementary constraints at lower energy should follow the detection of 47 Tucanae by the Fermi Large Area Telescope, but given the possible complexity of the emission in the GeV range, the connection to the VHE band cannot be assessed here.

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