Detection of High-Energy Gamma-Ray Emission from the Globular Cluster 47 Tucanae with Fermi

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We report the detection of gamma-ray emissions above 200 megaelectron volts at a significance level of 17σ from the globular cluster 47 Tucanae, using data obtained with the Large Area Telescope onboard the Fermi Gamma-ray Space Telescope. Globular clusters are expected to emit gamma rays because of the large populations of millisecond pulsars that they contain. The spectral shape of 47 Tucanae is consistent with gamma-ray emission from a population of millisecond pulsars. The observed gamma-ray luminosity implies an upper limit of 60 millisecond pulsars present in 47 Tucanae.

With their typical ages of $\sim 10^{10}$ years, globular clusters form the most ancient constituents of our Galaxy. They are seen throughout the electromagnetic spectrum, from radio waves up to x-ray energies, revealing their various stellar components. In particular, x-ray observations have shown that globular clusters contain considerably more close binary systems per unit mass than the galactic disc (*1*); this finding is interpreted as a result of frequent stellar encounters in their dense stellar cores (*2*). This scenario is strengthened by the observation that the number of low-mass x-ray binary systems containing neutron stars is directly correlated with the stellar encounter rate (*3*, *4*). These close binary systems may provide a source of internal energy stabilizing the cluster against collapse (*5*). Another consequence of this scenario is the presence of many millisecond pulsars (MSPs, also known as "recycled" pulsars); these are pulsars that were spun up to millisecond periods by mass accretion from a low-mass x-ray binary companion (*6*).

The only domain in which globular clusters have so far eluded detection is gamma rays. Recent observations with the Large Area Telescope (LAT) onboard the Fermi Gamma-ray Space Telescope have revealed gamma-ray pulsations from eight MSPs, establishing these objects as a class of high-energy gamma-ray sources (*7*, *8*). Most of the MSPs detected in gamma rays are within a distance of only a few hundred parsecs from the Sun, which implies that MSPs are rather faint objects with isotropic gamma-ray luminosities that generally do not exceed 10^{33} ergs s^{-1} (*8*). Placed at a distance of several kiloparsecs (the distance to the nearest globular clusters), it is unlikely, although not impossible, that individual MSPs are being detected in gamma rays. Globular clusters, however, may contain tens to several hundreds of MSPs (*9*), and their cumulative mag-

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netospheric emission is probably the first signature that would be picked out in gamma rays.

47 Tucanae (NGC 104) is one of the most promising candidates for high-energy gamma-ray emission because of the large number of known MSPs in the cluster and its relative proximity (4 kpc) (*10*). So far, 23 MSPs have been detected in 47 Tuc by radio and/or x-ray observations, and the total population is estimated to be 30 to 60 (*9*, *11*, *12*), although claims in the past reached up to 200 (*13*). We observed 47 Tuc with the LAT aboard Fermi during the continuous sky survey observations of the satellite. Our data cover the period 8 August 2008 to 3 April 2009 and correspond to 194.3 days of continuous observations, during which a total exposure of ~2 × 10^{10} cm^2·s (at 1 GeV) has been obtained for 47 Tuc. We restricted our analysis (*14*) to photon energies of >200 MeV, where our current knowledge of the instrument response implies systematic uncertainties that are <10% and where the photon energy dispersion caused by incomplete energy measurements becomes negligible.

The LAT image of the region around 47 Tuc shows a bright and isolated gamma-ray source that is consistent with the location of the globular cluster (Fig. 1) (*14*). We determined the gamma-ray spectrum of the LAT source by maximum likelihood fitting of the emission in 10 logarithmically spaced energy bins covering the interval 200 MeV to 10 GeV (Fig. 2). The spectrum reveals a relatively flat spectral energy distribution with a clear cutoff at energies above a few GeV; it is well fitted by an exponentially cut-off power law that provides a 3σ improvement upon a simple power law, with best-fitting spectral index $\Gamma = 1.3 \pm 0.3$ and cutoff energy $E_{\rm cut} = 2.5^{+1.6}_{-0.8}$ GeV. The systematic uncertainty in the spectral index is estimated to be 0.1; that in the cutoff energy is estimated to be 0.3 GeV. By integrating the best-fitting model over the energy range 100 MeV to 10 GeV, we determined the integral photon flux in this band to be 2.6 (±0.8) × 10^{-8} photons cm^{-2} s^{-1}, which is slightly below the upper limit of 5 × 10^{-8} photons cm^{-2} s^{-1} reported by EGRET (*15*–*17*). The photon flux corresponds to an energy flux of 2.5 (±0.4) × 10^{-11} ergs cm^{-2} s^{-1}. The systematic uncertainty in our fluxes is estimated to be <10%. The overall detection significance of the source amounts to 17σ.

We searched for time variability of the gamma-ray signal by dividing our data set into equally sized time bins of durations 1 day, 1 week, 2 weeks, and 1 month. We detected no source at the location of 47 Tuc in any of the daily or weekly time bins, which indicates that the observed emission did not arise from short-duration flares. The LAT source was significantly detected in all 2-week and monthly time bins at a comparable flux level, which suggests that the source was steady over the period of observation. Using ephemerides from (*18*) for 21 MSPs in 47 Tuc, we searched for gamma-ray pulsations in our data without finding any significant detection. The observed gamma-ray signal thus does not appear to be dominated by a single (or a few) known gamma-ray pulsars in 47 Tuc; this is in line with the absence of a single particularly powerful MSP in the cluster (*14*).

Pulsed gamma-ray curvature radiation (and eventually inverse Compton scattering) arising near the polar cap and/or in an outer magnetospheric gap in MSPs has been proposed as a possible source of high-energy photons in globular clusters (*19*–*22*). The main unknowns of this scenario are the exact site of gamma-ray production (polar cap versus slot gap or outer gap), the efficiency η_γ with which the spin-down power is converted into gamma-ray luminosity, and the total number of MSPs in the cluster. The eight galactic MSPs that have so far been detected by Fermi (*8*) have a mean spectral index of $\langle\Gamma\rangle = 1.5 \pm 0.4$ and a mean cutoff energy of $\langle E_{\rm cut}\rangle = 2.8 \pm 1.8$ GeV, similar to what we found for the 47 Tuc source. Cumulative gamma-ray emission from MSPs in 47 Tuc is thus a plausible explanation for the observed signal.

Under this hypothesis, we estimate η_γ from the gamma-ray flux of 47 Tuc by taking the average spin-down power to be $\langle\dot{E}\rangle = 1.8\ (\pm 0.7) \times 10^{34}$ ergs s^{-1} (*14*) and keeping the total number of MSPs in 47 Tuc as a parameter of the solution. For a distance to 47 Tuc of 4.0 ± 0.4 kpc (*10*), the measured energy flux of 2.5 (±0.4) × 10^{-11} ergs cm^{-2} s^{-1} converts into an isotropic gamma-ray luminosity of $L_\gamma = 4.8\ (\pm 1.2) \times 10^{34}$ ergs s^{-1}, which results in $\eta_\gamma = 0.12\ (\pm 0.05)\,\overline{f}_\Omega/N_{23}$, where $\overline{f}_\Omega$ is an average geometrical correction factor that accounts for non-isotropic emission (*23*) and N_{23} is the number of MSPs in 47 Tuc in units of 23. $N_{23} \geq 1$ implies that $0.12\ (\pm 0.05)\,\overline{f}_\Omega$ is an upper limit on the spin-down to gamma-ray luminosity conversion efficiency in 47 Tuc; this is consistent with the predicted conversion efficiency of 6.1% based on a model of the expected gamma-ray emission from a population of MSPs in 47 Tuc in the framework of a fully three-dimensional general-relativistic polar cap pulsar model (*22*). It is also compatible with the estimated conversion efficiency of ~10% of (*24*) that was derived in the framework of a space charge-limited flow acceleration polar cap model.

The conversion efficiencies of the eight galactic MSPs detected by Fermi cover the range from $0.02 f_\Omega$ to $1.0 f_\Omega$ with a mean value of $\langle\eta_\gamma\rangle = 0.14\,\overline{f}_\Omega$ (*8*), which is larger than the upper limit we derive for 47 Tuc. However, the MSPs that have been detected so far by Fermi are faint gamma-ray sources, forming a sample that is likely biased toward intrinsically bright

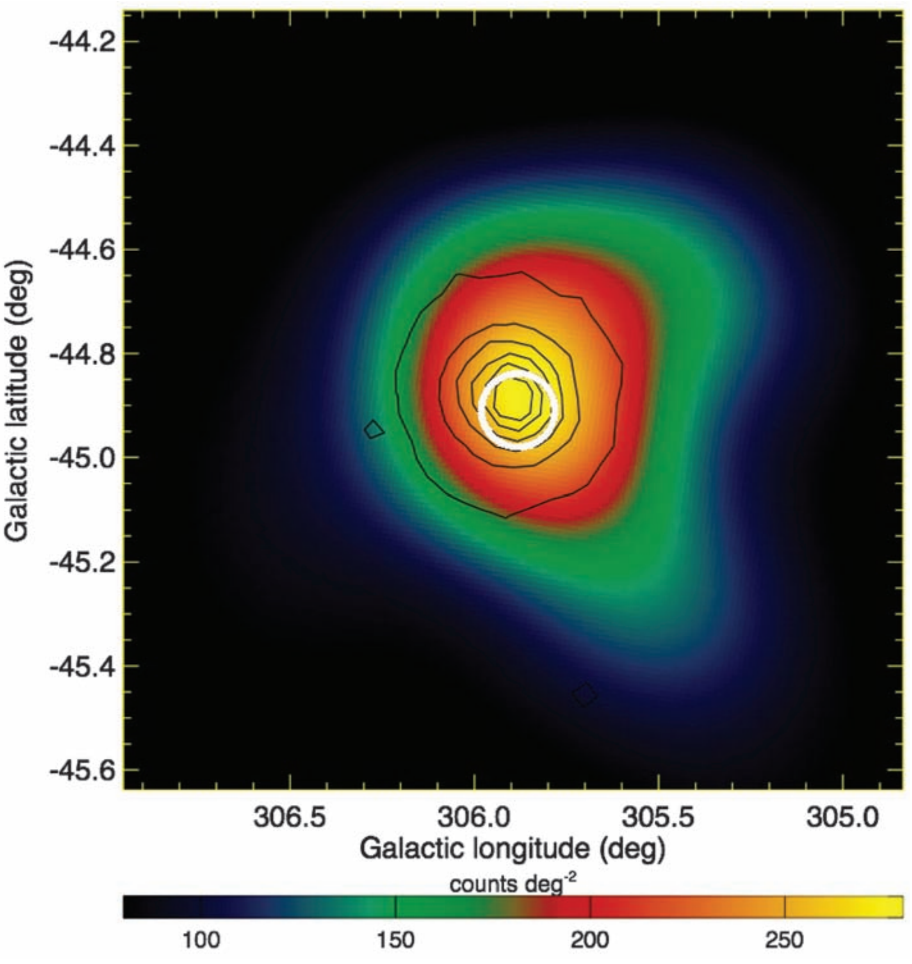

Fig. 1. Fermi LAT gamma-ray image (200 MeV to 10 GeV) of a 1.5° × 1.5° region centered on the position of 47 Tuc. The map was adaptively smoothed by imposing a minimum signal-to-noise ratio of 5. A total of ~290 counts were detected from the gamma-ray source. Black contours indicate the stellar density in 47 Tuc as derived from DSS2 red plates (*30*). The white circle shows the 95% confidence region for the location of the gamma-ray source. The position of the LAT source coincides with the core region of 47 Tuc.

objects or objects for which the beam orientation is favorable. Selecting only the nearest MSPs should reduce this bias, because for close objects a larger fraction of the MSP parameter space is accessible to Fermi. Taking only the three nearest MSPs from the Fermi sample (which also corresponds to the three nearest known MSPs) results in a mean spin-down to gamma-ray luminosity conversion efficiency of $\langle\eta_\gamma\rangle = 0.08\bar{f}_\Omega$, considerably lower than the global average. Taking the five nearest MSPs results in $\langle\eta_\gamma\rangle = 0.10\bar{f}_\Omega$. Both values are consistent with our upper limit on 47 Tuc. Thus, our data show no evidence for differences in the gamma-ray efficiencies of MSPs in globular clusters with respect to objects observed in the galactic field.

Assuming that the gamma-ray efficiencies of MSPs in 47 Tuc are equal to those of the nearby galactic field sample, and also assuming that their average geometrical correction factors $\bar{f}_\Omega$ are the same, we obtained an estimate of the total number of MSPs in 47 Tuc. Taking the mean $\langle\eta_\gamma\rangle = 0.08\bar{f}_\Omega$ that we obtained for the sample of the nearest galactic MSP as the most conservative estimate, we converted the observed gamma-ray efficiency $\eta_\gamma = 0.12\ (\pm 0.05)\ \bar{f}_\Omega/N_{23}$ for 47 Tuc into $N_{23} = 1.5 \pm 0.6$. Formally, this corresponds to a 95% confidence interval of 7 to 62 MSPs in 47 Tuc (assuming that uncertainties are Gaussian), which is consistent with the range of 45 to 60 MSPs estimated on the basis of x-ray observations obtained previously with Chandra (*11*). The x-ray and gamma-ray constraints thus suggest a population of about 50 to 60 MSPs in 47 Tuc. This is a factor of ~2 above the number of known radio MSPs in the cluster and also well above the upper limit of 30 radio MSPs estimated to be present in 47 Tuc (*25*), constraining the radio beaming fraction to >0.5 times that of the gamma-ray beaming. We recall that this result relies on an estimate of the average gamma-ray efficiency of MSPs. We obtained this efficiency from a sample of galactic field MSPs and selected the value that appears to be the least biased and that is the most conservative in the sense that it produces the largest estimate for the number of MSPs in 47 Tuc. The smallness of the gamma-ray sample of MSPs, however, implies that the average gamma-ray efficiency is still uncertain and likely biased.

It has been suggested that MSPs may produce relativistic magnetized winds that, when interacting with stellar winds or winds from other MSPs, create shocks that are capable of accelerating electrons and positrons into the GeV-TeV regime (*26*, *27*). These high-energy particles may eventually undergo inverse Compton scattering on stellar and cosmic microwave background radiation, producing detectable fluxes of GeV-TeV gamma-ray emissions. The expected gamma-ray emission from 47 Tuc has been modeled in this scenario by Bednarek and Sitarek (*26*), who predicted 100 MeV to 10 GeV photon fluxes on the order of 10^{-8} photons cm^{-2} s^{-1} and energy fluxes on the order of ~3×10^{-11} ergs cm^{-2} s^{-1}, which are on the order of the values we observed using the LAT. However, Bednarek and Sitarek assumed for their calculations that the total power injected as relativistic electrons and positrons amounts to 1.2×10^{35} ergs s^{-1}, which corresponds to a mean MSP spin-down power of $\langle\dot{E}\rangle = 5.2 \times 10^{35}$ ergs s^{-1} under the assumptions that the total number of MSPs in 47 Tuc amounts to 23 objects and that the average energy conversion efficiency from the pulsar winds to relativistic electrons and positrons amounts to 1% (*22*, *26*). This spin-down power is about a factor of 30 larger than the average spin-down luminosity of MSPs in 47 Tuc (*14*), which suggests that the gamma-ray flux estimates of (*26*) are overly optimistic and that the contribution of pulsar wind interactions to the gamma-ray emission observed by LAT is probably negligible.

Furthermore, the pulsar wind interaction model of (*26*) predicts gamma-ray spectra that extend well above 1 GeV into the TeV domain, with possible spectral turnovers and breaks above ~100 GeV. These high cutoff energies are at odds with our observed spectral break energy in the GeV range. To explain a GeV spectral break in the pulsar wind interaction model, the maximum energy of the accelerated particles should be limited to a few GeV; this scale is below the injection energies expected for electrons and positrons from the inner pulsar magnetospheres, which may range up to TeV energies (*27*). Consequently, pulsar wind interactions should play a minor role in the acceleration of electrons and positrons in 47 Tuc. This is consistent with the model of (*22*), which suggests that the direct conversion efficiency of spin-down energy into gamma rays, η_γ, is considerably larger than the efficiency $\eta_{e\pm}$ for electron and positron production. We cannot exclude, however, the possibility that pulsar wind interactions contribute at a low level to the gamma-ray signal we detected from 47 Tuc. Because TeV gamma-ray emission from 47 Tuc has not yet been detected (*28*), we cannot place firm constraints on that contribution.

Until now the study of close binary systems in globular clusters mainly has relied on x-ray observations. Such studies, however, are hampered by the fact that a large variety of binary systems emit x-rays [cataclysmic variables (CVs), low-mass x-ray binaries (LMXBs), chromospherically active main-sequence binaries (BY Dras), and MSPs] and that it is difficult to assess the nature of the sources from x-ray observations alone [however, see (*11*)]. X-ray studies must therefore be backed up by multiwavelength identification programs that help to disentangle these source populations. High-energy gamma-ray observations are unique in that they should be sensitive mainly to the pulsar populations. This is illustrated by Fermi observations of our own Galaxy that have revealed that pulsars form the largest and most luminous point-source population in this energy domain. No CVs, LMXBs, or BY Dras have so far been detected in high-energy gamma rays (*29*). It thus seems rather likely that pulsars (and MSPs in particular) are also the primary population of gamma-ray sources in globular clusters.

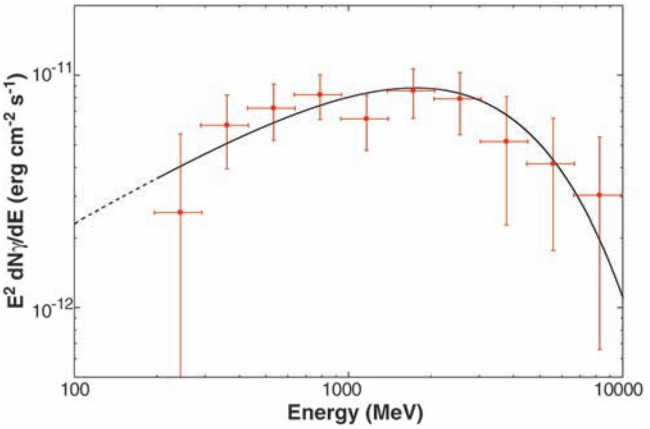

Fig. 2. Spectral energy distribution (E^2dN_γ/dE) of the Fermi source seen toward 47 Tuc. The solid line shows the fit of an exponentially cut-off power law obtained for the energy range 200 MeV to 20 GeV. The dashed line indicates the extrapolation of the fit to 100 MeV.

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Figs. S1 and S2
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A Population of Gamma-Ray Millisecond Pulsars Seen with the Fermi Large Area Telescope

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Pulsars are born with subsecond spin periods and slow by electromagnetic braking for several tens of millions of years, when detectable radiation ceases. A second life can occur for neutron stars in binary systems. They can acquire mass and angular momentum from their companions, to be spun up to millisecond periods and begin radiating again. We searched Fermi Large Area Telescope data for pulsations from all known millisecond pulsars (MSPs) outside of globular clusters, using rotation parameters from radio telescopes. Strong gamma-ray pulsations were detected for eight MSPs. The gamma-ray pulse profiles and spectral properties resemble those of young gamma-ray pulsars. The basic emission mechanism seems to be the same for MSPs and young pulsars, with the emission originating in regions far from the neutron star surface.

After the discovery of pulsars, 15 years elapsed before instrumental and computing advances enabled the first radio detections of neutron stars with millisecond spin periods (*1*). Similarly, 17 years after the launch of the Compton Gamma Ray Observatory (CGRO), the Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope (formerly GLAST) is now revealing new classes of GeV gamma-ray pulsars. Here, we report LAT detections of pulsed gamma rays from eight galactic millisecond pulsars (MSPs), confirming the marginal detection of PSR J0218+4232 made using the Energetic Gamma Ray Experiment Telescope (EGRET) detector on CGRO (*2*), and including the first MSP seen with the LAT, PSR J0030+0451 (*3*). A companion article (*4*) describes the discovery of 16 young pulsars on the basis of their gamma-ray emission alone. In addition, the LAT has detected about 20 young, radio-loud pulsars (*5*–*7*). The AGILE collaboration has recently detected pulsed gamma-ray emission from an MSP in the globular cluster M28 (*8*).

The Fermi LAT measurements of pulsars in all three of these categories will clarify how neutron stars accelerate the charged particles that radiate at gamma-ray and lower energies. Observed pulse profiles depend on the beam shapes and how they sweep across Earth; comparison of the radio, x-ray, and gamma-ray profiles constrains models of beam formation in pulsar magnetospheres. For gamma-ray pulsars, the high-energy emission dominates the power of the observed electromagnetic radiation (*9*). Consequently, gamma rays provide a probe of these cosmic accelerators. Millisecond pulsars shine for billions of years longer than do normal pulsars. We now know that they can radiate brightly in gamma rays.

The LAT images the entire sky every 3 hours at photon energies from 20 MeV to >300 GeV (*10*). Incident gamma rays convert to electron-positron pairs in tungsten foils, leaving tracks in single-sided silicon strip detectors that provide the photon direction. A hodoscopic CsI calorimeter samples the photon energy, and charged particles are rejected through the use of information from a segmented scintillator array.

MSPs form a distinct class, with small spin periods ($P < 30$ ms) and minuscule braking rates ($\dot{P} < 10^{-17}$). Most are in binary systems. The idea that they have been spun up by the torque resulting from accretion of mass from their companions (*11*) is supported by the recent observations reported in (*12*). MSPs are 10^8 to 10^{10} years old, whereas the young gamma-ray pulsars are 10^3 to 10^5 years old. Their surface magnetic fields are a factor of 10^4 weaker than when the neutron star first formed. However, both the rate of rotational kinetic energy loss, $\dot{E} = 4\pi^2 I\dot{P}/P^3$ (on the assumptions of dipole magnetic fields and a neutron star moment of inertia $I = 10^{45}$ g·cm²), and the magnetic field at the light cylinder, $B_{\mathrm{LC}} = 4\pi^2(3I\dot{P}/2c^3P^5)^{1/2}$ (where c is the speed of light), are comparable to those of newly formed pulsars (*13*). On the basis of theoretical models of gamma-ray emission from MSPs, it