Astron. Astrophys. 350, 847–851 (1999)

ASTRONOMY AND ASTROPHYSICS

New observational constraints on hard X-/γ-ray millisecond pulsar emission from 47 Tucanae

C. Ferguson, F. Lei, A.J. Dean, A.J. Bird, and J.J. Lockley

Department of Physics and Astronomy, University of Southampton, UK (cf@astro.soton.ac.uk)

Received 10 June 1999 / Accepted 30 August 1999

Abstract. Recent X-/γ-ray observations with the Rossi X-ray Timing Explorer (RXTE) of 47 Tuc (NGC 104) are used to compare different models of millisecond pulsar emission. Data from both the Proportional Counter Array and the High Energy X-ray Timing Experiment are presented, covering a total energy range of 2–250 keV.

A new upper limit on the hard X-/γ-ray emission from 47 Tuc is set, suggesting that the isolated millisecond pulsars may be non–emitting or very weak X-ray sources. The current binary X-ray emission theory is consistent with this result with some modification.

Timing analysis reveals no periodic pulsations in the data, further suggesting that isolated millisecond pulsars are very weak X-ray emitters.

Key words: X-rays: stars – stars: binaries: general – stars: pulsars: general – Galaxy: globular clusters: individual: 47 Tuc

1. Introduction

The large stellar populations of globular clusters are believed to contain many millisecond pulsars. In the conventional scenario, a neutron star either captures a main sequence or (sub)giant star via tidal interaction or forms a binary via an exchange encounter (Bhattacharya and van den Heuvel 1991). Either option results in a close binary system. Millisecond pulsars are assumed to be the end products of low mass X-ray binary evolution, where an old neutron star is spun up to a millisecond period during an accretion phase.

In binary millisecond pulsars it has been suggested that hard X-ray emission may arise by interaction of the pulsar wind with gaseous material evaporated from the companion (Tavani 1993). Eventually, evaporation of the companion or ionisation of the binary can lead to the formation of isolated millisecond pulsars. In isolated millisecond pulsars, hard X-rays may arise from magnetospheric emission (Chen 1991) but this has not been observationally verified.

Alternatively, Rudak & Dyks (1998) have suggested that isolated millisecond pulsars will be weak γ-ray emitters. They propose a simplified polar cap model where the energy of the electrons in the plasma has to be above $E_{\rm min}$ and below the lower of $E_{\rm max}$ or $E_{\rm w}$:

$$E_{\rm w} = 1.2 \times 10^7 B_{12} P^{-2} {\rm MeV} \quad (1)$$

$$E_{\rm max} = 4.6 \times 10^7 B_{12}^{1/4} P^{-1/8} {\rm MeV} \quad (2)$$

$$E_{\rm min} = 1.2 \times 10^7 B_{12}^{-1/3} P^{1/3} {\rm MeV} \quad (3)$$

$E_{\rm min}$ represents the minimum energy that accelerated electrons require for pair creation. $E_{\rm max}$ is the maximum energy the electrons can be accelerated to, determined by curvature cooling in a purely dipolar magnetic field. $E_{\rm w}$ is the absolute maximum energy to which the electrons can be accelerated and is determined by the potential drop across the polar cap. A consequence of this model is that when $E_{\rm max} < E_{\rm min}$ there will be no emission i.e. the pulsar is "dead".

47 Tuc is a good candidate to search for hard X-ray emission from millisecond pulsars because it is nearby (4.6 kpc), it has a relatively dense core and radio results have shown it contains at least eleven millisecond pulsars (Manchester et al. 1990; Manchester et al. 1991; Robinson et al. 1995; see Table 1). A previous observation using the Burst and Transient Source Experiment (BATSE) by Ford et al. (1996) set an upper limit of 5.8×10^{34} erg s^{-1} to the persistent emission from 47 Tuc in the energy band 20–120 keV. This corresponds to 19 isolated millisecond pulsars (Chen 1991) or up to 46 binary millisecond pulsars (Tavani 1993) and is not inconsistent with radio results. However, the High Energy X-ray Timing Experiment (HEXTE) on board RXTE should offer a gain in sensitivity over the BATSE search in this energy band and thus constrain the limits even more tightly.

1.1. Previous soft X-ray observations

Hertz & Grindlay (1983) observed 47 Tuc as part of a globular cluster survey using both the High Resolution Imager (HRI) and the Imaging Proportional Counter (IPC) on Einstein. These resulted in detections of 47 Tuc with different luminosities. The HRI limit is 3.9×10^{34} erg s^{-1} and the IPC limit is 7.1×10^{33} erg s^{-1}, both in the 0.5–4.5 keV band. Aurière et al. (1989) used recalibrated Einstein IPC data to obtain an X-ray spectrum of 47 Tuc, and to study its variability. Depending on

Send offprint requests to: C. Ferguson

Table 1. Summary of Sources Detected in Radio surveys of 47 Tuc. Naming convention follows that of Robinson et al. (1995) B0021-72C etc. * - No unique orbital solution calculated.

Source	Period (ms)	Binary Status	Orbital Period
47 Tuc C	5.756780	No	
47 Tuc D	5.357573	No	
47 Tuc E	3.536329	Yes	2.2568 days
47 Tuc F	2.623579	No	
47 Tuc G	4.040379	No	
47 Tuc H	3.2103	Yes	*
47 Tuc I	3.484993	Yes	0.226 days
47 Tuc J	2.100633	Yes	0.1206 days
47 Tuc L	4.3462	Probably	*
47 Tuc M	3.676644	No	
47 Tuc N	3.053954	No	

Table 2. Comparison of RXTE results with previous surveys. (u - upper limit, d - detection). Luminosity is given in erg s^{-1}. We give a 2σ upper limit in the 20–120 keV band. See text for references.

Energy Range	Luminosity	Instrument
0.75–1MeV	2.67×10^{35}	COMPTEL (u)
40–100keV	2×10^{35}	SIGMA (u)
100MeV $>$	1.2×10^{35}	EGRET (u)
20–120keV	5.8×10^{34}	BATSE (u)
20–120keV	5.4×10^{33}	HEXTE (2σ u)
0.5–4.5keV	3.9×10^{34}	Einstein HRI (d)
0.5–4.5keV	7.1×10^{33}	Einstein IPC (d)
0.5–4.5keV	7.65×10^{33}	PCA (d)
0.5–2.5keV	4×10^{33}	ROSAT HRI (d)
0.5–2.5keV	5.39×10^{33}	PCA (d)
2–10keV	5.35×10^{33}	PCA (d)

the model fit, the luminosity (0.2–4 keV) is 7–8.7×10^{33} erg s^{-1}. The core source X0021.8–7221 has pulsations at 120.2 seconds and at 4.58 seconds, which they suggest implies it is a cataclysmic variable.

Hasinger et al. (1994) observed 47 Tuc with the ROSAT High Resolution Imager (HRI). They detected four sources in the core and four within 90″, as well as finding some evidence for diffuse emission. The luminosities they estimate for the core sources are higher than those expected for cataclysmic variables and they suggest that the X–ray sources are neutron star binaries. This observation has recently been re–analyzed and combined with new data by Verbunt & Hasinger (1998). Five sources are now detected in the core, with a further four within 2′. They also produced light curves for the five core sources, two of which (X9 and X10) show a high degree of variability. They identify the source X9 (X0021.8–7221) with a blue variable star and suggest that it is a soft X-ray transient.

1.2. Previous hard X-/γ-ray observations

Barret et al. (1993) used the SIGMA γ-ray telescope, on board the Soviet GRANAT spacecraft, to observe 47 Tuc in the energy range 40–1200 keV. They found no significant emission above the 2σ confidence level in any of their nine observations. Similarly, in the sum of their observations, they detect no flux from 47 Tuc. From their observations, they obtain a 2σ upper luminosity limit of 2×10^{35} erg s^{-1}, in the 40–100 keV band.

47 Tuc has been observed with three of the instruments on board the Compton Gamma Ray Observatory (CGRO): the Energetic Gamma Ray Experiment Telescope (EGRET) uses spark chambers to provide coverage over the energy range 30 MeV to 30 GeV; the imaging Compton telescope (COMPTEL) uses Compton scattering to image over the energy range 1 MeV to 30 MeV; and the Burst and Transient Source Experiment (BATSE) is an all–sky monitor sensitive in the energy range 20 keV to 1 MeV.

Michelson et al. (1994) used the EGRET all sky survey to search a number of globular clusters for emission at $>$100MeV. They found no significant emission from 47 Tuc above the 2σ confidence level and placed an upper limit to the luminosity of 1.2×10^{35} erg s^{-1}.

O'Flaherty et al. (1995) observed 47 Tuc with the COMPTEL instrument. They detected no emission, and so set a 2σ upper limit to the luminosity in the 0.75–30 MeV band of 9.63×10^{35} erg s^{-1}. They also set an upper limit over the 0.75–1 MeV band of 2.67×10^{35} erg s^{-1}.

Ford et al. (1996) used BATSE to monitor 27 globular clusters in the band 20–120 keV for 1400 days. They detect no emission (outburst or persistent) from 47 Tuc, and set a 2σ upper limit of 5.8×10^{34} erg s^{-1}. Using a photon spectrum of E^{-2}, and models by Chen (1991) and Tavani (1993), they set upper limits on the number of isolated and binary millisecond pulsars of 19 and 46 respectively.

Table 2 summarizes the previous X-ray observations of 47 Tuc.

2. RXTE observations

This paper details observations carried out in December 1996 using both the Proportional Counter Array (PCA) and the High Energy X-ray Timing Experiment (HEXTE) on board RXTE. The total live time accumulated was ~65,000 seconds, which was split over a period of five days. The PCA is an array of five proportional counters, covering an energy range of 2–60 keV with timing resolution down to 1 μs. The HEXTE instrument consists of two clusters of phoswich detectors, which cover an energy range of 15–250 keV with timing resolution down to 8 μs.

2.1. Spectral analysis

PCA data reduction followed the standard method provided by the Guest Observer Facility (GOF 1998). Lightcurves and spectra were extracted using a Good Time Interval (GTI) to filter the data. The GTI identifies periods of good data e.g. when more than 30 minutes have passed since the satellite went through the South Atlantic Anomaly or the elevation is high enough to avoid Earth occultation. The PCA detectors have 3 layers of anodes, and extractions were carried out firstly over all 3 layers and then over the top-layer only. For low-energy X-rays, the top-layer only data are expected to have a higher signal-to-noise ratio. Background files were generated using the L7 background models. Both the raw and background files were corrected for dead time, and then the appropriate response matrices were generated.

HEXTE analysis involved separating the data into on-source and off-source files, extracting spectra and correcting for dead time. For each of the HEXTE clusters the spectra were combined to form a final spectrum. The response matrices were downloaded from the legacy site (legacy 1998). The response files used were *hexte_97mar20c_pwa.rmf* and *hexte_97mar20c_pwb013.rmf*.

2.2. Timing analysis

A search was undertaken for periodicities in the range 0.1 milliseconds to 40 kiloseconds. This period range was split into two parts which were analysed in different ways. Firstly, the longer period range (320–40,000 s) was analysed using an epoch folding technique. Secondly, the short period range (0.0001–320 s) was analysed using a Fast Fourier Transform technique.

For the long period searches we used standard–2 format PCA data, extracted to form a lightcurve, using the same Good Time Interval as for the spectral analysis. Only top-layer detections in the range 2–10 keV were extracted to maximize the signal-to-noise ratio. The background files were the same ones used for the spectral analysis, and the extraction criteria were the same as the standard–2 PCA data. Both raw and background lightcurves were dead time corrected. The background lightcurve was then subtracted from the raw lightcurve, creating the source lightcurve. Barycentric correction was then applied to the source lightcurve.

For the short period searches, the recipe given by the Guest Observer Facility (RXTE GOF 1998) was followed using Goodxenon format PCA data. This was filtered to give continuous cleaned data over the energy range 2–10 keV. A Fast Fourier Transform was then used to search the data for periodicities.

3. Results

3.1. Spectral analysis results

Fig. 1 shows the PCA (top-layer only) and HEXTE data plotted together. A model consisting of a 3 keV bremsstrahlung with an absorption column of $2.4\times10^{20}\mathrm{N_H/cm^2}$ and a power-law (with the same absorption column) of index 1.76 has been fitted. The bremsstrahlung component dominates at lower energies (similar to previous X-ray results; Hasinger et al. 1994), whilst the power-law dominates at higher ones (as suggested by theory; Tavani 1993). However, the power-law seems to be a poor fit to the HEXTE data. Preliminary analysis of BeppoSAX data of the same field (Ferguson et al., in preparation) suggests this may be due to contamination by a nearby source. The PCA (top-layer only) count rate over the energy range 2 to 10 keV is 0.826 cts s^{-1}. The luminosities calculated from this model in various bands are shown compared with previous studies in Table 2.

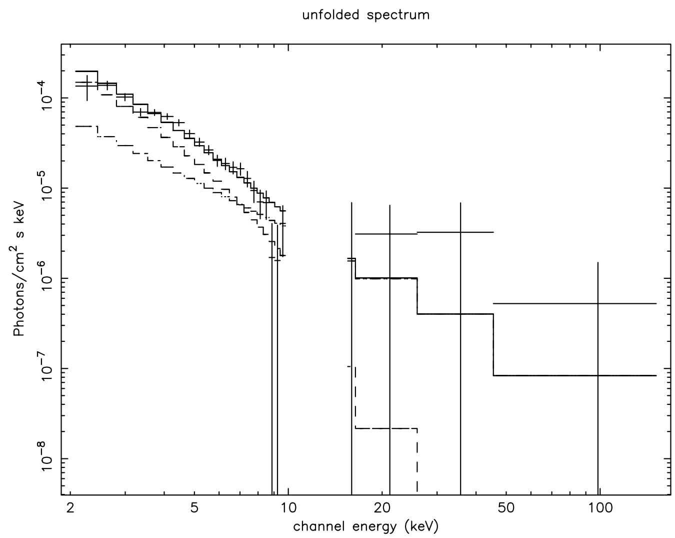

Fig. 1. Combined PCA and HEXTE spectrum.

To compare these results with the BATSE observations of Ford et al. (1996), the energy band 20–120 keV is considered. The HEXTE spectrum at these energies shows emission at $\sim$1.4σ. This is not significant enough to be classed as a detection of 47 Tuc and so we set a 2σ upper limit of 5.4×10^{33} erg s^{-1} for use in our analysis. The upper limit on luminosity derived from the model is a factor of 10 lower than the previous upper limit from the BATSE survey (Ford et al. 1996).

3.2. Timing analysis results

In both the power spectrum and epoch folding searches, the analysis of Leahy et al. (1983) was followed. No peaks at 90% confidence were found in any of the power spectra or epoch folding searches. The upper limits on pulse amplitudes are summarized in Table 3. Any periods present would have to have amplitudes less than about 6% of the 2–10 keV flux to have avoided detection.

4. Discussion

Using the method of Chen (1991) the approximate luminosities of the 6 isolated millisecond pulsars are calculated (Table 4).

The total luminosity of the isolated millisecond pulsars in the 20–120 keV band in 47 Tuc, as estimated from Chen (1991), is 1.9×10^{34} erg s^{-1}. This is a factor of 3.5 higher than the new upper limit of 5.4×10^{33} erg s^{-1}, and clearly indicates some over estimation of luminosity in this model. Probably the assumption that millisecond pulsars are Vela–type pulsars is in error. The total spin–down power derived for a globular cluster seems reasonable, but the conversion efficiency of millisecond pulsars may have been over-estimated. Recent work by Zhang & Cheng (1998) indicates that millisecond pulsars have lower conversion efficiencies than had been expected.

Table 3. Summary of the timing analysis upper limits over the 2–10 keV region. The upper limit in amplitude is given as a percentage of the 2–10 keV flux. The corresponding upper limit in Luminosity is also shown.

Frequency (Hz)	Period (s)	Amplitude (%)	Luminosity (erg s^{-1})
2.5×10^{-5}–1.02×10^{-3}	39940–980	4.68	2.5×10^{32}
1.01×10^{-3}–2.56×10^{-3}	990–390	2.98	1.59×10^{32}
2.56×10^{-3}–5.243	390.625–0.1907	2.2	1.18×10^{32}
5.12–5.24288×10^{3}	0.195–1.9×10^{-4}	6.0	3.21×10^{32}

Table 4. The Periods and Luminosities of the isolated millisecond pulsars in 47 Tuc, as calculated following Chen (1991).

Source	Period (ms)	Luminosity erg s^{-1}
47 Tuc C	5.756780	4.49×10^{33}
47 Tuc D	5.357573	4.18×10^{33}
47 Tuc F	2.623579	2.04×10^{33}
47 Tuc G	4.040379	3.15×10^{33}
47 Tuc M	3.676644	2.87×10^{33}
47 Tuc N	3.053954	2.38×10^{33}

Table 5. $E_{\rm min}$ and $E_{\rm max}$ calculated using the known period and an assumed magnetic field of 10^8G.

	P(ms)	$E_{\rm min}$(MeV)	$E_{\rm max}$(MeV)
C	5.76	4.6×10^7	8.8×10^6
D	5.36	4.5×10^7	8.8×10^6
F	2.62	3.6×10^7	9.7×10^6
G	4.04	4.1×10^7	9.2×10^6
M	3.68	4×10^7	9.3×10^6
N	3.05	3.7×10^7	9.5×10^6

Table 6. $E_{\rm min}$ and $E_{\rm max}$ calculated using the known period and an assumed magnetic field of 5×10^8G.

	P(ms)	$E_{\rm min}$(MeV)	$E_{\rm max}$(MeV)
C	5.76	2.7×10^7	1.3×10^7
D	5.36	2.6×10^7	1.32×10^7
F	2.62	2.1×10^7	1.45×10^7
G	4.04	2.4×10^7	1.37×10^7
M	3.68	2.3×10^7	1.39×10^7
N	3.05	2.2×10^7	1.42×10^7

Table 7. $E_{\rm min}$ and $E_{\rm max}$ calculated using the known period and an assumed magnetic field of 10^9G.

	P(ms)	$E_{\rm min}$ (MeV)	$E_{\rm max}$(MeV)
C	5.76	2.15×10^7	1.56×10^7
D	5.36	2.1×10^7	1.57×10^7
F	2.62	1.65×10^7	1.72×10^7
G	4.04	1.9×10^7	1.63×10^7
M	3.68	1.85×10^7	1.65×10^7
N	3.05	1.74×10^7	1.69×10^7

In Tables 5, 6 and 7 the model of Rudak & Dyks (1998) is used to estimate $E_{\rm min}$ and $E_{\rm max}$ for the isolated millisecond pulsars in 47 Tuc. Only in the case of 47 Tuc F (with B = 10^9G) will $E_{\rm max}$ be greater than $E_{\rm min}$. Therefore, for most reasonable values of B the isolated millisecond pulsars in 47 Tuc would be "dead".

In the case of the binary millisecond pulsars, following Ford et al. (1996), the estimated luminosity is 1.3×10^{33} erg s^{-1}, which implies a maximum of 4 binary millisecond pulsars. This result is not inconsistent with the observed number of binaries in 47 Tuc.

The estimated millisecond pulsar luminosity of Ford et al. (1996) can be reduced to match our observation in a number of ways.

Firstly, the calculated flux in Ford et al. (1996) is for energies above 20 keV. The calculated photon flux above 120 keV is 1.2×10^{-6} photons cm^{-2} s^{-1}, giving a flux in the 20–120 keV band of 5.9×10^{-6} photons cm^{-2} s^{-1}. This would reduce the luminosity in 47 Tuc for each binary millisecond pulsar to $\sim 1 \times 10^{33}$ erg s^{-1} giving a maximum of 5 binaries in the cluster.

More important is the assumption that the fraction of the total shock luminosity radiated in this band is close to one for an average ablating millisecond pulsar. In such a narrow band as 20–120 keV, the fraction of shock luminosity radiated may be significantly lower than this.

A further assumption is that the spin–down power is $\sim 10^{34}$ erg s^{-1}. A smaller value, $\sim 5 \times 10^{33}$ erg s^{-1}, would make the theoretical predictions of the binary millisecond pulsar model (Tavani 1993) compatible with the X-ray observations. The spin–down power is sensitive to age, and the old age of the 47 Tuc millisecond pulsars could result in a smaller spin–down power than assumed by Ford et al. (1996).

5. Conclusions

A new 2σ upper limit of 5.4×10^{33} has been set on the persistent hard X-/γ-ray emission from 47 Tuc. This is a factor of 10 lower than the previous limit of Ford et al. (1996).

Unsurprisingly, due to the large numbers of super-imposed periods in 47 Tuc and the weakness of the X-ray sources, no evidence of millisecond pulsations is seen. A limit on the amplitude of any pulsations in the 2–10 keV band of 3.21×10^{32} erg s^{-1} is set. This further suggests that the isolated millisecond pulsars are weak emitters.

It seems the model of Chen (1991) over–estimates the luminosity of the isolated millisecond pulsars in 47 Tuc. For most reasonable values of magnetic field, it is unlikely (using the

Rudak & Dyks (1998) model) that there will be any γ-ray emission from the isolated millisecond pulsars in 47 Tuc.

The upper limit (20–120 keV) to the persistent emission from 47 Tuc, could be consistent with the binary model of Tavani (1993), if the isolated millisecond pulsar model of Rudak & Dyks (1998) is accepted. This result requires that there are no other sources of hard X-/γ-rays in the cluster and requires changes to the assumptions used by Ford et al. (1996).

The possible discovery of nine new binary millisecond pulsars in 47 Tuc (Camilo et al. 1999) will put more constraints on the binary X-ray emission model. This new result implies the luminosity of a binary millisecond pulsar is a factor of three less than that calculated by Ford et al. (1996). The model of Tavani (1993) could be compatible with these results if:

- the fraction of shock luminosity radiated in this band is $\sim 1/3$,
- or the pulsar is not enshrouded in the material evaporated from the companion,
- or the efficiency of conversion of pulsar wind energy to X-/γ-rays is lower than expected.

A more thorough exploration of binary millisecond pulsar X-ray emission theory, in the light of new observations, is left to a future paper.

Acknowledgements. The authors would like to thank the anonymous referee for many helpful comments, which undoubtedly improved this manuscript. This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center.

References

Aurière M., Koch-Miramond L., Ortolani S., 1989, A&A 214, 113
Barret D., Mandrou P., Denis M., et al., 1993, ApJ 405, L59
Bhattacharya D., van den Heuvel E.P.J., 1991, Phys. Rep. 203, 1
Camilo F., Lorimer D.R., Freire P., Lyne A.G., 1999, ApJ, submitted
Chen K., 1991, Nat 352, 695
Ferguson C., Lei F., Dean A.J., 1999, in prep.
Ford E., Kaaret P., Harmon B.A., Tavani M., Zhang S.N., 1996, ApJ 467, 272
Hasinger G., Johnston H.M., Verbunt F., 1994, A&A 288, 466
Hertz P., Grindlay J.E., 1983, ApJ 275, 105
Leahy D.A., Darbro W., Elsner R.F., et al., 1983, ApJ 266, 160
Legacy download site, ftp://legacy.gsfc.nasa.gov/xte/calib_data/
Manchester R.N., Lyne A.G., D'Amico N., et al., 1990, Nat 345, 598
Manchester R.N., Lyne A.G., Robinson C., et al., 1991, Nat 352, 219
Michelson P.F., Bertsch D.L., Brazier K., et al., 1994, ApJ 435, 218
O'Flaherty K.S., Bennett K., Diehl R., et al., 1995, A&A 297, 290
Robinson C., Lyne A.G., Manchester R.N., et al., 1995, MNRAS 274, 547
RXTE GOF web site, http://heasarc.gsfc.nasa.gov/docs/xte/xte_1st.html
Rudak B., Dyks J., 1998, MNRAS 295, 337
Tavani M., 1993, ApJ 407, 135
Verbunt F., Hasinger G., 1998, A&A 336, 895
Zhang L., Cheng K.S., 1998, MNRAS 294, 177