

## Discovery of a quiescent neutron star binary in the globular cluster M 13

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**Abstract.** We have discovered with XMM-Newton an X-ray source in the core of the globular cluster M 13, whose X-ray spectral properties suggest that it is a quiescent neutron star X-ray binary. The spectrum can be well fitted with a pure hydrogen atmosphere model, with  $T_{\infty} = 76 \pm 3$  eV,  $R_{\infty} = 12.8 \pm 0.4$  km and an X-ray luminosity of  $7.3 \pm 0.6 \times 10^{32}$  ergs s<sup>-1</sup>. In the light of this result, we have discovered a strong correlation between the stellar encounter rate and the number of quiescent neutron stars found in the ten globular clusters observed so far by either XMM-Newton or Chandra. This result lends strong support to the idea that these systems are primarily produced by stellar encounters in the core of globular clusters.

**Key words.** globular clusters – stars: neutron – X-rays: general

### 1. Introduction

Globular clusters (GCs) are known to harbour both bright and dim X-ray sources. Bright X-ray sources with luminosities above  $\sim 10^{36}$  ergs s<sup>-1</sup> are commonly agreed to be neutron star Low-Mass X-ray Binaries. There are twelve such sources known in GCs; 11 of them have shown type I X-ray bursts, the unmistakable signature of an accreting neutron star. On the other hand, dim GC X-ray sources are much more numerous (for example, dozens of such objects exist in  $\omega$  Cen, see Gendre et al. 2003), but their nature is still debated. They have maximum luminosities of  $\sim 10^{33}$  ergs s<sup>-1</sup> and there is growing evidence that they are a variety of different objects. Some of the fainter ones have been identified as Cataclysmic Variables or active binaries (RS CVn, BY Dra). Others, have been associated with radio millisecond pulsars (MSPs) (e.g. Grindlay et al. 1991). Some of the “brighter” of the dim X-ray sources have recently been proposed to be quiescent neutron star X-ray binaries (qNSs) on the basis of their X-ray spectral properties (47 Tuc, Grindlay et al. 2001;  $\omega$  Cen, Rutledge et al. 2002, Gendre et al. 2002; NGC 6440, Pooley et al. 2002b).

Outside GCs, qNSs are found to have soft X-ray spectra and luminosities up to  $10^{33}$  ergs s<sup>-1</sup> (e.g. Kong et al. 2002). During outbursts, reactions, deep in the crust, heat the neutron star (Brown et al. 1998). Between outbursts, the heated surface radiates a thermal spectrum, emitted by a neutron star hydrogen atmosphere (NSA). The thermal component of the quiescent X-ray spectra of two neutron star X-ray binaries which are not in a globular cluster (Aql X-1 and Cen X-4) are well fitted by NSA models, providing strong support for this theory.

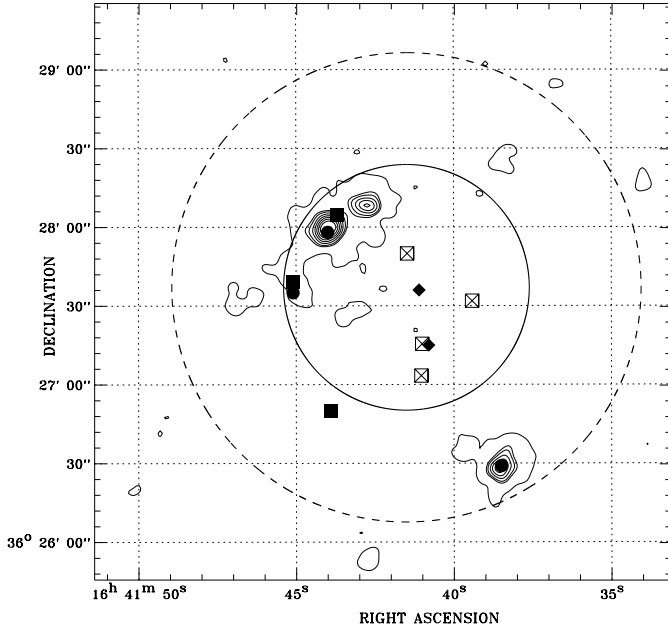
In contrast, quiescent black hole transients have hard power law like spectra and low luminosities (down to  $10^{30}$  ergs s<sup>-1</sup>). Accretion via an advection dominated flow is thought to be responsible for the observed hard and weak emission (Kong et al. 2002; Hameury et al. 2003, and references therein). Thus the combination of a soft thermal X-ray spectrum and a luminosity above  $\sim 10^{32}$  ergs s<sup>-1</sup> has been used to claim the detection of qNSs in GCs. The existence of such systems in GCs was first proposed by Verbunt et al. (1984). It is generally assumed that they are formed through stellar encounters (tidal capture or exchange encounters) in the dense cores of GCs (see Hut et al. 1992, for a review).

ROSAT HRI and PSPC observations (Fox et al. 1996; Verbunt 2001), revealed several dim X-ray sources in M 13. The HRI observations showed two core sources, whose unresolved PSPC spectrum could be fitted with a 0.9 keV thermal bremsstrahlung model ( $L_{0.5-2.5 \text{ keV}} \sim 2.5 \times 10^{32}$  ergs s<sup>-1</sup>). M 13 is somewhat remarkable as it contains also four MSPs (Taylor et al. 1993; Ransom et al. 2002).

### 2. Observations and results

The globular cluster M 13 was observed by the XMM-Newton EPIC cameras on 2002 January 28 and 30, using the Full Frame Window and a medium filter. The total length of the observation was  $\sim 37$  ks. We analyzed the data using the XMM-Newton Science Analysis Software (SAS) version 5.3.3. Initially we considered the two segments of the observation separately. We used the SAS tasks *emchain* and *epchain* to calibrate the raw data, flag bad pixels and filter for non-astrophysical events. The background was found to be variable and relatively high. Removing the periods of unstable background left 9 and 8 ks

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**Fig. 1.** A contour image of the center of the field of view of M 13. The core and half mass radii are shown as solid and dashed lines, respectively. Previous identifications are: ROSAT sources (filled circles, Verbunt 2001); faint UV sources (filled squares, Ferraro et al. 1997); radio objects (open squares, Johnston et al. 1991); and MSPs with known positions (filled diamonds, Taylor et al. 1993) (the most central MSP has positional uncertainties larger than the image displayed). All other objects have uncertainties smaller than the symbol size.

respectively. The filtered event files were merged using *merge* and then we extracted images and spectra.

The source detection procedure used is described in Gendre et al. (2003). Briefly, it combines a wavelet detection algorithm applied to a 0.5–5.0 keV band image, and a maximum likelihood fitting of the source candidates. A conservative maximum likelihood threshold of 12 was chosen. The absorption-corrected limiting flux is  $3.6 \times 10^{-15}$  ergs s $^{-1}$  cm $^{-2}$  corresponding to a luminosity of  $2.6 \times 10^{31}$  ergs s $^{-1}$  for a source located at the center of the field of view having a 0.6 keV blackbody spectrum.

We found an extended source within the core radius. The extension appeared to be due to two sources that were not quite resolved. The MOS cameras have the advantage of having a smaller pixel size than the PN camera: 1.1'' for MOS (Turner et al. 2001) as oppose to 4.1'' for PN (Strüder et al. 2001). When processing the event file, the task *emevents* converts the event position (RAWX and RAWY) into camera coordinates in units of 0.05''. This step includes randomization (within a CCD pixel) of the event to avoid the Moiré effect. By default, the *xmmselect* task, assumes a binning factor of 87 to produce MOS images with the same pixel size as PN images. We have produced MOS images with a binning size of 20, corresponding to a pixel size of 1''. The image smoothed with a simple 2D-Gaussian of  $\sigma = 2.0''$  is shown in Fig. 1.

To summarize, we detected 2, 5 and 77 sources within the core radius, half mass radius and field of view respectively. Using the Log  $N$ –Log  $S$  curve of extragalactic sources reported in Hasinger et al. (2001) and the limiting flux in the

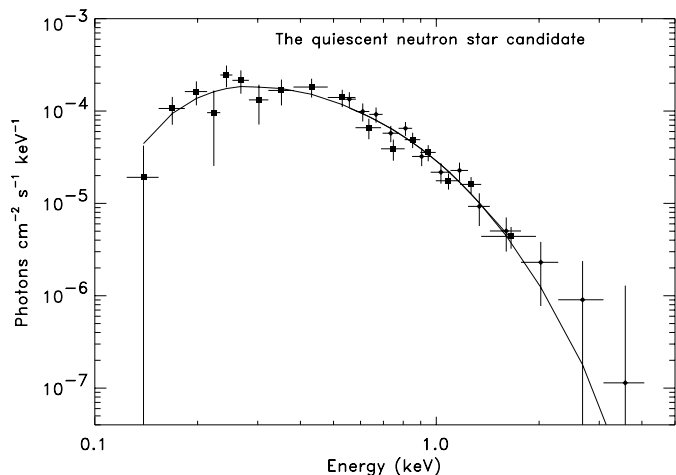
**Table 1.** XMM-Newton sources detected within twice the half mass radius (HMR) (CR = Core Radius). The positional error includes the statistical error (90% confidence, estimated from *srcmatch*) and a systematic error of 4'' (Jansen et al. 2001).

RA h m s	Dec ° ' ''	Error ''	Location
16 41 37.9	36 28 26.3	7.94	HMR
16 41 42.7	36 28 06.7	4.60	CR
16 41 43.8	36 27 58.6	4.27	CR
16 41 46.8	36 27 29.5	5.93	HMR
16 41 49.0	36 26 44.6	7.53	2 × HMR
16 41 38.3	36 26 27.0	4.50	HMR
16 41 49.9	36 26 18.7	7.38	2 × HMR
16 41 42.5	36 25 53.0	6.83	2 × HMR

three regions given above, we determined the expected number of background sources to be 0, 1 and 72, respectively. The positions and errors of sources found within twice the half-mass radius are given in Table 1. It goes beyond the scope of this paper to investigate the error box content of each of the XMM-Newton sources. It is however worth mentioning that only 10 of the 11 ROSAT sources that should have been detected by XMM-Newton, given the limiting flux and field of view of the observation, were detected. We failed to detect the ROSAT source Gb. This source must have therefore varied in flux by at least a factor 10 between the ROSAT and XMM-Newton observations.

The two core sources are separated by only 15'' (see Fig. 1). One is the ROSAT source Ga (Verbunt 2001). The other should have been detected by ROSAT, if its flux had not varied. We reanalyzed the HRI data and determined that the source flux must have varied by a factor  $\sim 2$  between the ROSAT and the XMM-Newton observations.

Two sources lying so close together complicates the spectral analysis. Normally, spectra are accumulated over a region of radius of 0.7' to include 85% of the source photons. Such an extraction region is 3 times larger than the source separation. Using a radius of 0.7', we have extracted the spectrum of the brighter source by masking out a region of radius 15'', offset by 5'' from the fainter source. We have estimated that only 6% of the counts in the spectrum of the brighter source come from the fainter source, insufficient to affect the results of our spectral analysis. Spectra were extracted from the EPIC-PN and the two MOS cameras. We binned these spectra to contain at least 20 net counts per bin and generated ARF and RMF files with the SAS tasks *arfgen* and *rmfgen*. The spectra are extremely soft, with  $\sim 90\%$  of the counts below 2 keV. We have tried to fit the combined spectrum with different single component models (blackbody and thermal bremsstrahlung). Absorption by the interstellar medium was included in the fit but was found to be consistent with the expected value from the optical extinction towards the cluster ( $1.1 \times 10^{20}$  cm $^{-2}$ , Djorgovski 1993). We also tried to fit the spectrum with a pure hydrogen NSA model (Pavlov et al. 1992; Zavlin et al. 1996). This model provides the best fit to our data. Assuming a neutron star mass of  $1.4 M_{\odot}$ , we derived  $T_{\infty} = 76_{-3}^{+3}$  eV



**Fig. 2.** The unfolded EPIC-PN (diamonds) and ROSAT-PSPC (squares) spectra of the qNS candidate and the best fit NSA model, one of the best qNS spectra to date.

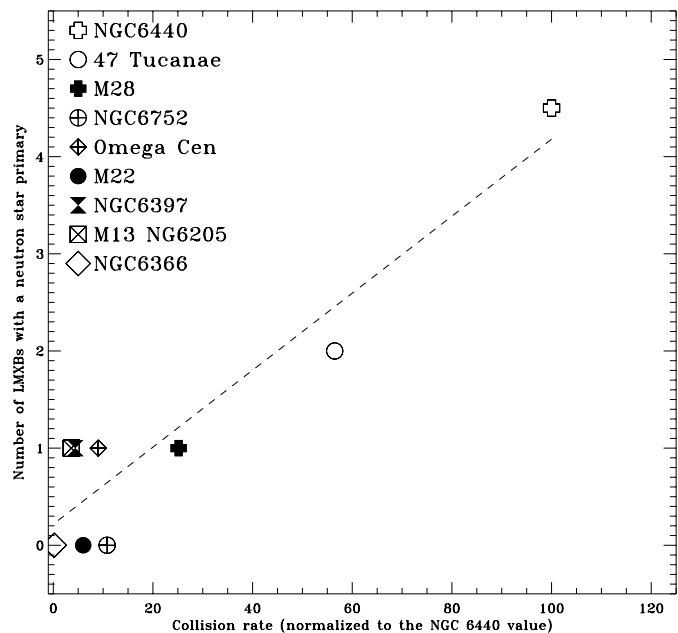
and  $R_\infty = 12.8^{+0.4}_{-0.4}$  km, with a  $\chi^2_\nu = 0.55$  (15 degrees of freedom (d.o.f.)). These parameters are similar to those determined for the proposed qNS in  $\omega$  Cen (Rutledge et al. 2002; Gendre et al. 2003).

We have retrieved and reanalyzed the ROSAT PSPC archival observations of M 13 to determine whether the PSPC spectrum of source Ga could be fitted with the same model. A fit of the combined PSPC and XMM-Newton data revealed parameters consistent with those derived from the XMM-Newton data alone ( $\chi^2_\nu = 0.90$ , 26 d.o.f.). We present the unfolded combined EPIC-PN and ROSAT spectrum in Fig. 2. The luminosity derived for the NSA model is  $(7.3 \pm 0.6) \times 10^{32}$  erg s $^{-1}$  (0.1–5.0 keV), using the distance of 7.7 kpc (Harris 1999).

### 3. Discussion

The most likely interpretation of the nature of the softest source in M 13 is that it is a quiescent neutron star low-mass X-ray binary. This interpretation is supported by the luminosity of the source, the softness of its X-ray spectrum and the fact that a NSA model yields a good fit and plausible parameters (radius and temperature) for the neutron star. A reasonable question to ask is whether we expect such a system in M 13. In the disk, qNSs have a minimum X-ray luminosity of  $\sim 10^{32}$  ergs s $^{-1}$  (Narayan et al. 2002). As it has been already emphasized, if the same luminosity threshold also applies to globular cluster qNSs, the luminosity limit of XMM-Newton and Chandra observations (typically around  $10^{30}$ – $10^{31}$  ergs s $^{-1}$  at the cluster distances) allows one to detect all the qNSs present in globular clusters. In Table 2, we list the globular clusters already observed by either Chandra or XMM-Newton, together with the number of qNSs reported in the literature.

In globular clusters, the number of qNSs is expected to scale with the collision rate which is proportional to  $\rho_0^{1.5} r_c^2$  for virialized clusters, where  $\rho_0$  is the central density of the cluster and  $r_c$  its core radius (Verbunt 2002). These values taken from the Harris (1999) catalog are listed in Table 2. In Fig. 3,



**Fig. 3.** The number of qNSs versus collision rate ( $\rho_0^{1.5} r_c^2$ ), shown with a linear fit  $n_{\text{qNS}} \sim 0.04 \times \rho_0^{1.5} r_c^2 + 0.2$ . The collision rates have been normalized to 100 for NGC 6440.

**Table 2.** qNSs in GCs detected by Chandra or XMM-Newton. Parameters for the clusters are taken from the Harris (1999) catalog; the distance is given in kpc, the core radius in  $'$ . We indicate the log of the central density in units of  $L_\odot \text{pc}^{-3}$ .

Cluster	Distance (kpc)	Core radius	Central density	qNSs
47 Tuc	4.5	0.44	4.77	2
$\omega$ Cen	5.3	2.58	3.12	1
M 13	7.7	0.78	3.33	1
NGC 6366	3.6	1.83	2.42	0
NGC 6397	2.3	0.05	5.68	1
NGC 6440	8.4	0.13	5.28	4-5
M 28	5.7	0.24	4.75	1
M 22	3.2	1.42	3.64	0
NGC 6752	4.0	0.17	4.91	0

References, top to bottom: Grindlay et al. (2001a, 2002); Rutledge et al. (2002), Gendre et al. (2003); this work; Webb et al. in preparation; Grindlay et al. (2001b); Pooley et al. (2002b); Becker et al. (2003); Webb et al. (2002); and Pooley et al. (2002a).

we plot the number of qNSs as a function of the collision rate, normalized so that the value for NGC 6440 is 100. There is a striking correlation between the number of qNSs and the collision rate. The presence of one qNS in M 13 is therefore not really surprising given that its collision rate puts the cluster in a region where one might expect either one or zero qNS. This remarkable correlation extends over more than 2 orders of magnitude and includes both core-collapsed and non core-collapsed clusters. This strongly supports the idea that qNSs are indeed primarily produced by stellar encounters in globular clusters (Verbunt 2002).

With the results of the observations reported here and the four already known MSPs, there are at least 5 neutron star systems in M 13. This makes M 13 the cluster with the fourth highest number of known neutron star systems. The retention of such a large number of neutron stars in a cluster with a relatively low central density remains to be explained (see for a comprehensive study of neutron star retention in globular clusters, Pfahl et al. 2002).

#### 4. Conclusion

We have reported the likely discovery of a quiescent neutron star in M 13. We have also shown for the first time that there is a strong correlation between the stellar collision rate and the number of qNSs in the 9 globular clusters observed by either XMM-Newton or Chandra. This lends strong support to the idea that these systems are primarily produced by stellar encounters in the core of globular clusters. More observations, in particular with XMM-Newton are being planned and should enable us to test the strength of this correlation.

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