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Nine X-ray sources in the globular cluster 47 Tucanae

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Abstract. We analyze ROSAT HRI observations obtained from 1992 to 1996 of the globular cluster 47 Tuc. Identifications of two X-ray sources with HD 2072 and with a galaxy, respectively, are used to obtain accurate ($< 2''$) positions of the X-ray sources in the cluster. We find possible optical counterparts, including the blue objects V 1 and V 2, for three X-ray sources in the core of 47 Tuc, but note that the probability of chance positional coincidence is significant.

One of the five sources previously reported by us to reside in the cluster core is found to be an artefact of misalignment between subsequent satellite pointings.

Key words: globular clusters: individual: 47 Tuc – X-rays: stars

1. Introduction

The cores of globular clusters harbour many interesting objects detected at different wavelengths, such as X-ray sources, ultraviolet and visual variables and blue stragglers, and radio pulsars. The sheer number density of stars in the cluster cores makes identification of sources detected in one wavelength range with those found at other wavelengths a daunting task, especially for X-ray sources whose positions are uncertain by more than an arcsecond at best.

As an example, X-ray sources detected in the core of 47 Tuc (Hasinger et al. 1994, henceforth called Paper 1) have been tentatively identified with a cataclysmic variable (Paresce et al. 1992), with blue stragglers (Meylan et al. 1996), and with a remarkable ultraviolet variable (Aurière et al. 1989, Minniti et al. 1997). These various options are possible due to the uncertainty in the absolute positions of the X-ray sources of about 5$''$.

In this paper we analyse three new ROSAT HRI observations of the globular cluster 47 Tuc, and re-analyse two. With use of the detailed astrometric study by Geffert et al. (1997) we try to obtain an absolute accuracy of the X-ray positions at the arcsecond level. In Sect. 2 we describe the observations and data analysis, and in Sect. 3 the results. A discussion follows in Sect. 4.

Table 1. Log of the ROSAT HRI observations of 47 Tuc. For each separate observation, indicated with a-f, the observation date(s), and exposure time are given. We further give the shift in $''$ applied to bring the observation to the X-ray coordinate frame of c. Observation e was timed to be quasi-simultaneous with a Hubble Space Telescope observation of 47 Tuc (see Minniti et al. 1997).

	observing period			$t_{\rm exp}$(s)	$\Delta_x('')$	$\Delta_y('')$
a	1992	Apr	2448732.006–32.020	1169	+2.5	−2.0
b	1992	May	2448764.413–65.424	3370	−2.0	+2.5
c	1993	Apr	2449094.509–96.913	13247		
d	1994	Nov	2449686.500–93.616	18914	+1.5	−1.5
e	1995	Oct	2450015.817–16.073	4579	+2.0	−0.5
f	1996	Nov	2450404.079–18.418	17542	+1.5	−1.0

2. Observations and data analysis

The log of the observations with the ROSAT X-ray telescope (Trümper et al. 1991) together with the high - resolution imager (HRI, David et al. 1992) is given in Table 1. For reasons explained below, we treat the April 1992 and May 1992 data as two separate observations (in contrast to Paper 1, where these were treated as a single observation). The data were reduced with the Extended Scientific Analysis System (EXSAS; Zimmermann et al. 1996).

The analysis of the new HRI data and reanalysis of the 1992/1993 data previously discussed in Paper 1, is done in several steps. First, we use the X-ray positions of four bright sources that are detectable in the separate observations to align all observations onto a single X-ray coordinate frame. We then use two optical identifications to convert the X-ray coordinate frame to J2000. The analysis of the sources is done separately for the region away from the cluster core, for which standard EXSAS techniques can be applied, and for the inner region, where we use contour maps and a multiple-source detection procedure to determine the individual source positions. The details of these procedures are as follows.

2.1. Co-alignment of the separate observations

Each photon is detected at a detector position (x, y). This position gives the distance to the center of the HRI detector. The pointing direction of the satellite provides the celestial coordi-

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nates for the center of the detector, and allows the conversion for each detector position to a celestial position. For this conversion a pixel size of $0.5''$ is assumed. The uncertainty in the pointing direction causes small shifts between the celestial positions derived from different observations. When different observations are added such shifts lead to smearing, and in extreme cases even doubling, of the sources. Before adding the separate observations, we therefore determine the shifts between them.

We first take account of the re-determination of the size of the HRI pixels to $0.4986''$ (Hasinger et al. 1998), by multiplying the x, y pixel coordinates of each photon with 0.9972. (This enables us to use the EXSAS software, which assumes $0.5''$ pixels, in the remaining reduction steps.) The main effect of this multiplication is to reduce the size of the image in celestial coordinates, and with it the distance between each source and the center of the image. We bin the data in bins of $5'' \times 5''$. We do a first source detection by comparing the counts in a box with those in the surrounding ring. The detection box is moved across the image. The sources thus detected are excised from the image, and a spline fit is made to the spatial distribution of the remaining photons. This fit is used as a background map for a second source detection pass, in which the excess of photons above the background is determined at each position. At the positions of all sources found in the two passes, we subsequently apply a maximum-likelihood algorithm which compares (a Gaussian approximation of) the point spread function of the XRT-HRI combination with the distribution of the individual photons, to determine the probability that a source is detected. We retain all sources with a likelihood parameter $L > 10$ (see Cruddace et al. 1988).

By comparison of the source lists of the separate observations, we find that four sources, listed as X 1, X 3, X 12 and X 14 in Paper 1 and in Table 2, are detected in each of the observations b,c,d,e; X 3, X 12 and X 14 are detected in observation f; and X 3 and X 14 in observation a. By weighted averaging of the position shifts of these sources, we determine the offsets between the celestial coordinate frame of observation c and that of each of the other observations. The offsets between each observation and observation c are listed in Table 1, rounded off to the nearest $0.5''$, and are well within the claimed positional accuracy of the HRI ($5''$). The offset between observations a and b is large, which is why we separate the 1992 April and May data.

The offsets listed in Table 1 are applied to bring all HRI observations to the X-ray coordinate frame of observation c. After this, all images are added. The exposure of the added image is 58,820 s. We repeat the source detection procedure explained above for the total image, to find the sources listed in Table 2 and shown in Fig. 1.

2.2. Conversion to the optical coordinate frame

In Paper 1 we suggest HD 2072 as identification for X 12; Geffert et al. (1997) suggest a galaxy at $\alpha(2000) = 00^h23^m 30.^s8$, $\delta(2000) = -72^\circ 20' 44.''0$ as identification for X 3, and give the position for HD 2072 as $\alpha(2000) = 00^h24^m\ 14.^s5$, $\delta(2000) = -71^\circ 58' 49.''1$. With a scale of $0.5''$ per pixel either of the two suggested identifications could be accepted, but not both. With the reduced scale of the X-ray image (see Sect. 2.1) we are now able to accept both identifications simultaneously, X 12 with HD 2072 and X 3 with the galaxy.

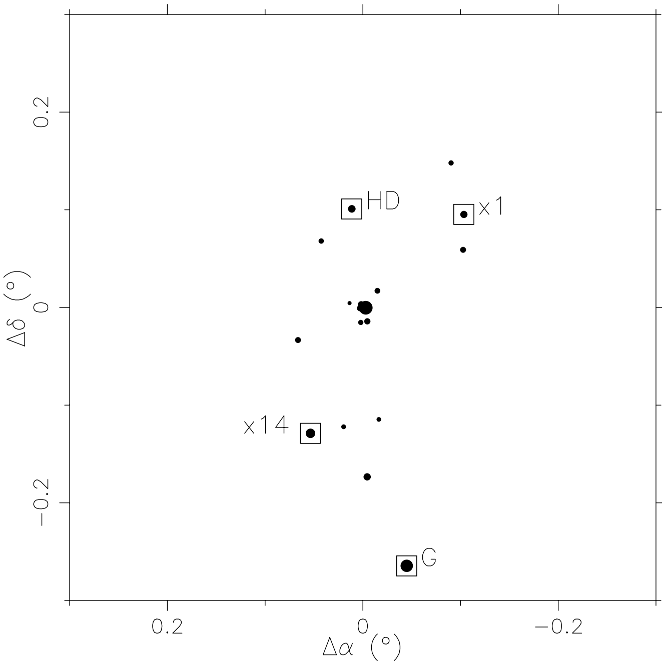

Fig. 1. The positions of the sources detected in our HRI observations of 47 Tuc. Each source is indicated with a •, the size of which is proportional to the logarithm of the observed countrate. Positions are with respect to the cluster center as determined by Guhathakurta et al. (1992): $\alpha_c(2000) = 00^h24^m5.^s83$, $\delta_c(2000) = -72^\circ 4' 51.''4$. The sources marked by squares are those used in co-aligning the separate observations; HD (=X 12) and G (=X 3) label the sources identified with HD 2072 and a galaxy, respectively, which have been used to determine the ('bore sight') correction applied to the X-ray positions to bring them to an optical coordinate frame.

The nominal X-ray positions of X 12 and X 3 were at $+0.11^s, +0.6''$ and $+0.14^s, 0.0''$, respectively, from the optical positions, well within the expected absolute accuracy of the X-ray positions. Taking into account the more accurate position of source X 12 we determine the overall shift between the X-ray frame of observation c and the J2000 coordinate frame as $-0.12^s (= -0.55''), -0.45''$. This correction has been applied to obtain the J2000 positions of the X-ray sources listed in Table 2

Combining the errors of about $1''$ of the location of the two X-ray sources in the X-ray frame with the error of about $1''$ in determining the shift between nominal X-ray positions and J2000, we estimate that the overall accuracy in aligning the X-ray coordinate frame to J2000 is better than $2''$.

2.3. Multiple source detection and variability

The standard analysis cannot disentangle sources that overlap. Fig. 2 shows that we have such a situation in the central region

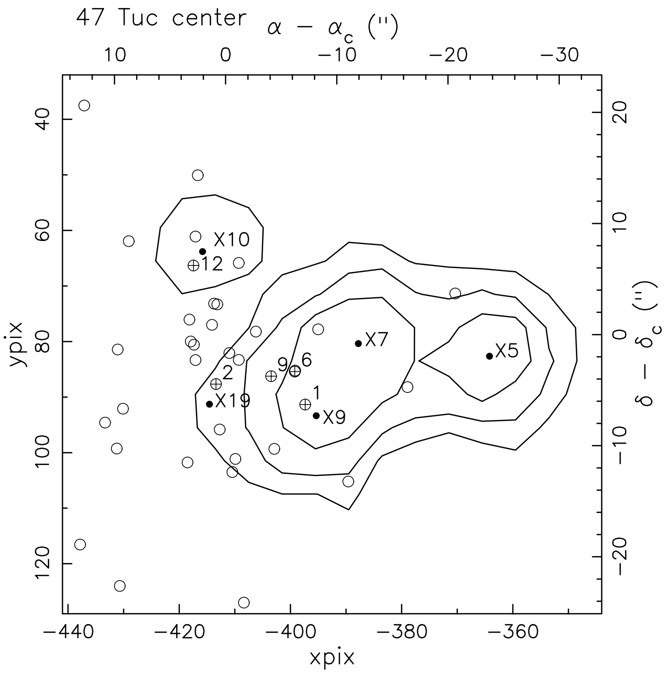

Fig. 2. X-ray image of the core of 47 Tuc. The solid lines show contour levels, determined on the basis of $3'' \times 3''$ bins, at 0.4, 0.16 and 0.064 times the maximum observed. •-s indicate the locations of the sources as determined with a multi-source algorithm. The lower and left axes refer to the detector coordinates; the upper and right axes give the distance with respect to the optical center of 47 Tuc as given by Guhathakurta et al. (1992). The uncertainty between the two coordinate systems is $\lesssim 2''$. Circles indicate locations of the optical variable and blue stars in the core of 47 Tuc, listed in Table 3 of Geffert et al. (1997). Some stars discussed in the text are inscribed with $+$, and labelled 1,2 for the blue objects V 1 and V 2, respectively; 6,9 for the variables AKO 6 and AKO 9, respectively; and 12 for variable 12 of Edmonds et al. (1996). The Einstein X-ray source (Grindlay et al. 1984) is not indicated, but coincides closely with V 1.

of 47 Tucanae. We therefore apply a multi-object algorithm to determine the number and positions of the sources in this region. This algorithm is described in Paper 1: briefly, it compares the predicted photon numbers with the observed ones for a binned data set, for an assumed point spread function. We use a bin size of $3'' \times 3''$. We vary the number of sources, and find that five sources, listed in Table 2, are required to explain the observation. Initial positions for the five sources were set by hand, on the basis of the contour plot shown in Fig. 2; the best positions of these sources, and their countrates, were determined with the multi-source algorithm. The fit for five sources is significantly better than a four-source fit in which source X 19 is omitted.

Table 2. Sources detected in the total image of 47 Tuc. The exposure time is 58820 s. The sources are ordered with respect to their right ascension. Sources X 1 to X 15 correspond to the sources in Hasinger et al. 1994; sources X 16 to X 21 are new. For each source we give the position, the statistical uncertainty in the position, the detected total number of counts, and for sources within $2'$ from the cluster center and therefore probably associated with 47 Tuc the X-ray luminosity in the $0.5-2.5$ keV band. Errors for source positions found with the multi-source fit program, marked with $*$, are mutually dependent, and hard to quantify. We estimate that they are $\sim 3''$ for X 19 and $2''$ for the others. In addition to the statistical uncertainty in the individual positions, the source positions are subject to a possible systematic uncertainty, which we estimate to be less than $2''$.

X	$\alpha(2000)$	$\delta(2000)$	Δ ($''$)	cts	$L_{\rm x}$(erg/s) ($\times 10^{32}$)
1	0 22 45.38	-71 59 8.8	0.7	89±11	
2	0 22 46.07	-72 1 19.8	1.0	52± 9	
16	0 22 55.48	-71 55 58.9	2.1	39± 9	
3	0 23 30.82	-72 20 44.5	1.0	720±32	
17	0 23 52.98	-72 11 44.3	1.4	31± 7	
4	0 23 54.06	-72 3 50.3	1.4	49± 9	0.6
5	0 24 0.93	-72 4 53.5	$*$	815.3±43	9.3
6	0 24 2.13	-72 5 42.7	0.8	59± 9	0.7
18	0 24 2.16	-72 15 16.1	1.5	91±12	
7	0 24 3.49	-72 4 52.4	$*$	1098.2±61	12.5
9	0 24 4.31	-72 4 58.9	$*$	696.4±52	8.0
19	0 24 6.39	-72 4 57.8	$*$	115.9±15	1.3
10	0 24 6.52	-72 4 44.1	$*$	178.8±19	2.0
11	0 24 7.34	-72 5 47.5	1.5	39± 8	0.4
12	0 24 14.49	-71 58 49.0	0.6	102±11	
13	0 24 16.17	-72 4 36.0	1.0	24± 6	0.3
20	0 24 20.80	-72 12 11.8	1.5	32± 7	
21	0 24 38.76	-72 0 46.5	0.9	41± 8	
14	0 24 47.23	-72 12 35.8	0.6	221±16	
15	0 24 57.20	-72 6 52.0	1.2	52± 9	

Finally, we investigate the source variability. For the sources outside of the core, we compare the countrates determined with the standard analysis of the individual observations b-f, as described above. If we allow that a source with an expected number of counts of $\lesssim 10$ can escape detection, we find that only two significant non-detections remain (see Fig. 3). Source X 1 is not detected in the November 1996 observation, whereas 27 counts are expected. Source X 18 is not detected in the April 1993 observation, whereas 20 counts are expected. We find no evidence for $> 2\sigma$ excess brightness in individual observations.

For the sources in the core, we fix the source positions as listed in Table 2, and on these positions determine the countrates for observations a and b combined, and for each of the observations c to f, with the multi-source algorithm. (Observations a and b are too short for separate countrate determinations.) The resulting individual countrates are shown in Fig. 3. Sources X 9 and X 10 are highly variable, the other sources are not significantly variable.

For conversion of the countrates to luminosities for the sources associated with 47 Tuc, we assume a 1 keV bremsstrahlung spectrum, absorbed by $N_{\rm H} = 2.4 \times 10^{20}\,{\rm cm}^{-2}$. At a distance of 4.6 kpc, 1 count per kilosecond in the HRI then corresponds to a luminosity at the source of 6.7×10^{31}erg/s. For the sources that are probably related to 47 Tuc, we use this conversion to compute the luminosities listed in Table 2.

3. Results

Our analysis leads to the detection of 20 sources in the direction of 47 Tuc. With the exception of X 8, all sources X 1-15

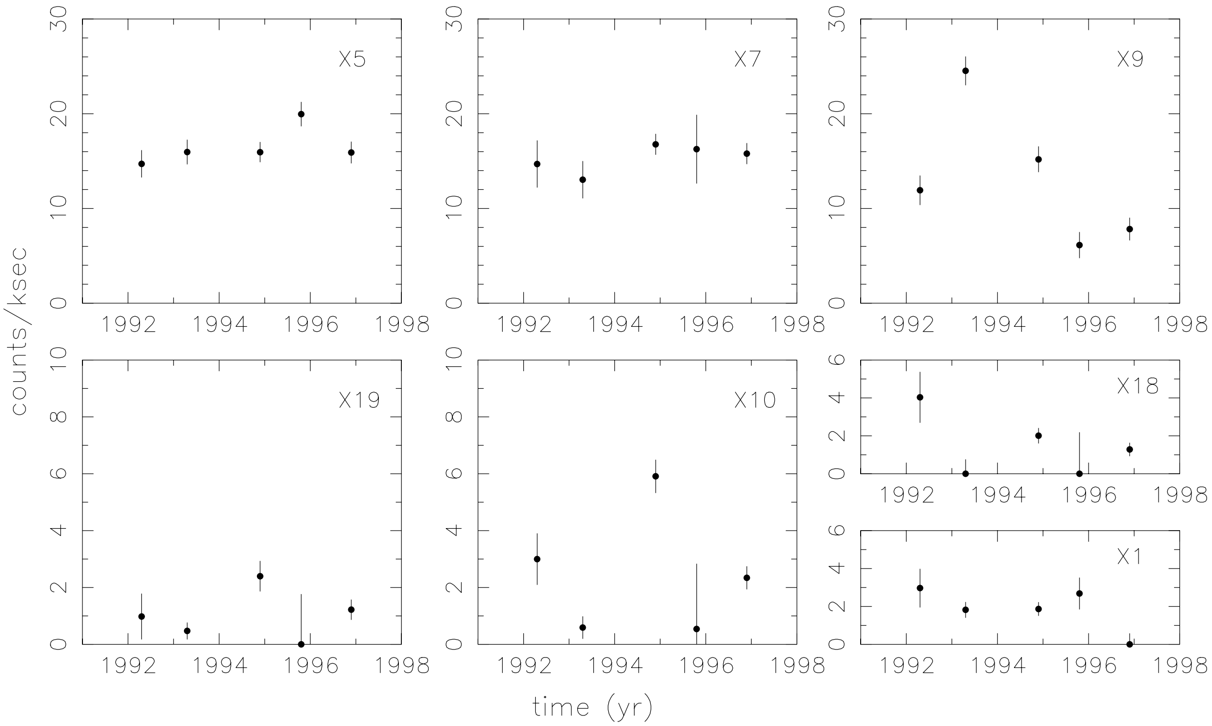

Fig. 3. Lightcurves of the five X-ray sources in the core of 47 Tuc, and of two variable sources probably not related to the cluster, X 1 and X 18. For non-detections of X 1 and X 18, an upper limit of 10 counts has been assumed; the 1992 points for these sources refer to the May observation only. Amongst the sources in the core, X 9 and X 10 are significantly variable.

discussed in Paper 1 are detected again; six new sources X 16-21 have been added, of which X 19 is in the core. Source X 8 was an artefact of the large relative shift between the April and May 1992 X-ray coordinate systems; now that we apply bore sight corrections to these observations separately, source X 8 is no longer found. Five sources are detected in the core (Fig. 2). Four sources are detected within $2'$ from the cluster center, rather more than expected randomly from the number of sources in the whole image; we conclude that these four sources are probably also related to 47 Tuc (see Fig. 1). Thus nine sources have been detected in the cluster.

3.1. Inside the core

In Fig. 2 we show the 5 X-ray sources in the core, together with the variable and blue stars listed by Geffert et al. (1997; their Table 3). The X-ray sources are plotted in the detector frame, the optical sources in the J2000 frame. The relative positions of these frames is accurate to better than $2''$. As a result, we can be more confident about possible optical counterparts to the X-ray sources than has been hitherto possible. AKO 6 and AKO 9 do not correspond to any of the detected X-ray sources. As these sources lie in the wings of the point spread functions of the detected X-ray sources, we cannot exclude that they emit X-ray flux at a lower level than the faintest detected X-ray source in the core, X 19. Positional coincidences within the error are found for V 1 and X 9, V 2 and X 19, and entries 29 and 31 from Table 3 in Geffert et al. (1997) with X 10.

V 1 was discovered by Paresce et al. (1992); according to Shara et al. (1996) V 1 is not significantly variable in the Hubble Space Telescope images. Thus the nature of the source is not clear. It may be a cataclysmic variable; its magnitudes are also compatible with those of a low-mass X-ray binary in a quiescent state. The ultraviolet flux reported by Paresce et al. (1992) corresponds to an AB_ν magnitude, corrected for the reddening towards 47 Tuc, of $AB_\nu \simeq 20.5$. The position of V 1 coincides within the accuracy with X 9, and also with the position of the X-ray source detected in 47 Tuc with Einstein (Grindlay et al. 1984). Both the Einstein observations (Aurière et al. 1989) and our ROSAT HRI observations (Fig. 3) show that the X-ray flux is variable by a factor ~ 3.

To investigate the nature of X 9 and V 1 we compare its visual magnitude and X-ray flux with those of cataclysmic variables from the Rosat All Sky Survey in Fig. 4. We estimate the countrate in channels 50–201 of the PSPC by multiplying the HRI countrate listed in Table 2 with a factor 2; and assume that the visual magnitude equals the AB_ν ultraviolet magnitude (as is often, but not always, the case for cataclysmic variables; see e.g. Verbunt 1987). We see in Fig. 4 that the ratio of the X-ray flux to the optical flux is rather high for a cataclysmic variable; even at the lowest measured X-ray flux of X 9, the X-ray to optical flux ratio is higher than that of any cataclysmic variable detected in the Rosat All Sky Survey. If V 1 is identical to X 9, we suggest therefore that it is a low-mass X-ray binary in a low state, i.e. the accreting object is a neutron star. Two soft X-ray transients in their quiescent state, Cen X-4 and Aql X-1, are

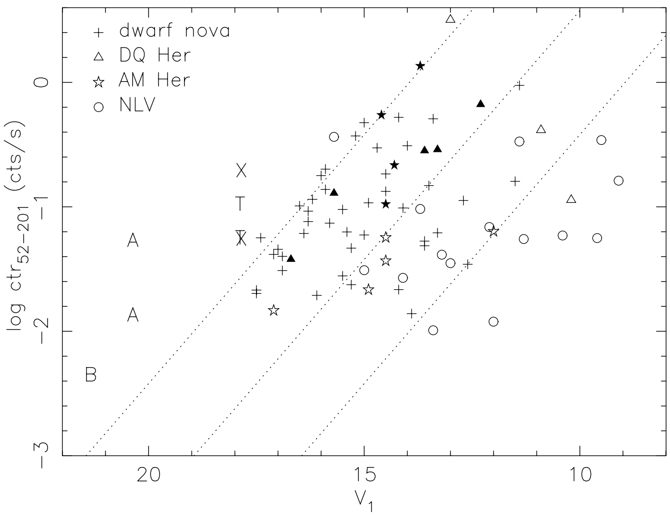

Fig. 4. ROSAT PSPC countrates of cataclysmic variables detected in the ROSAT All Sky Survey, as a function of visual magnitude. The data are from Verbunt et al. (1997), except that we take $V_1 = 15.9$ for BZ UMa. (Index 1 indicates the magnitude at which the system is most frequently found, MAG1 in Ritter 1990.) The dashed lines correspond to a constant ratio of X-ray to ultraviolet/optical flux. Different symbols indicate dwarf novae, AM Her and DQ Her type systems, and other cataclysmic variables ('nova like variables'); solid symbols indicate systems detected first in X-rays, and subsequently identified with cataclysmic variables ('X-ray selected systems'). We also show with A and B the estimated positions in this diagram for X 9 (at low and high observed countrate) and X 19, if we assume that these may be identified with V 1 and V 2, respectively. T and X indicate the locations of Aql X-1 and Cen X-4, respectively, in two observations at quiescence, corrected for interstellar absorption (optical data from Van Paradijs 1995; X-ray data from Verbunt et al. 1994, Campana et al. 1997).

also shown in Fig. 4; their X-ray to optical flux ratio is similar to those of V 1/X 9.

V 2 is a blue variable detected twice at a high level about 4 magnitudes above its quiescent level (Paresce & De Marchi 1994, Shara et al. 1996). In the ultraviolet, its quiescent AB_ν magnitude is $AB_\nu \simeq 21.5$. Its position coincides within the accuracy with X 19. Assuming again that the PSPC countrate is about twice the HRI countrate, and that the $V \simeq AB_\nu$, we show the location of V 2 and X 19 in Fig. 4. If V 2 and X 19 are identical, than the ratio of X-ray to optical flux is higher also for this system than for any cataclysmic variable detected in the ROSAT All Sky Survey, and similar to those of Cen X-4 and Aql X-1 in quiescence.

Entries 29 and 31 of Table 3 in Geffert et al. (1997) are nos. 1030 and 1286 of De Marchi et al. (1993), and both are blue stragglers. Entry 31 of Geffert et al. (1997) corresponds to binary no. 12 in Edmonds et al. (1996). The binary period is 0.69 days, or possibly 1.38 days; the nature of the binary is not clear. Further study of these systems is required before one of them can be identified with X 10.

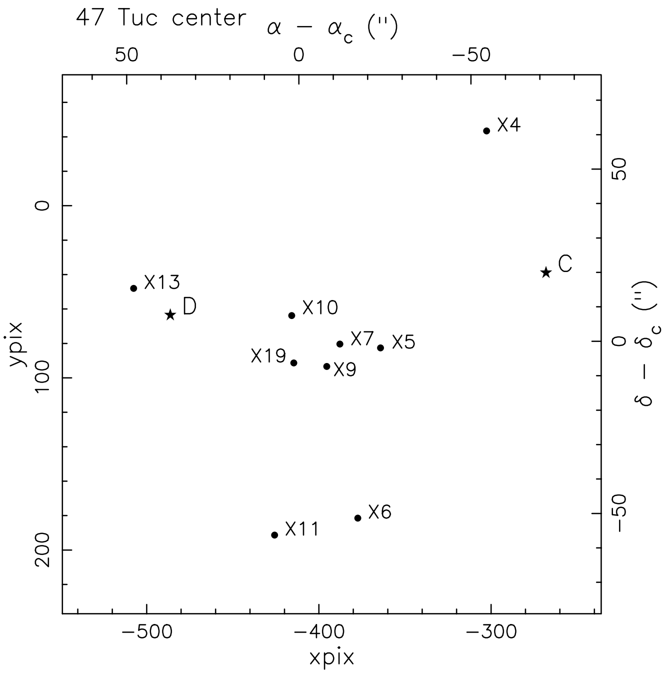

Fig. 5. Location of the X-ray sources in and near the core of 47 Tuc, compared with the two known positions of radio pulsars 47 Tuc C and 47 Tuc D.

A third blue variable has been found in the core of 47 Tuc by Shara et al. (1996). The nature of this variable, V 3, is not known. From Fig. 3c in Shara et al. (1996) we estimate that V 3 is about $9.4''$ North of V 2; and about $0.8''$ East. This is close to X 10, but too far for V 3 to be a candidate for identification with X 10.

The two brightest constant sources X 5 and X 7 cannot be identified with any of the blue and variable stars known in the core of 47 Tuc. It is remarkable that the Einstein satellite did not detect these sources, but only the variable source X 9. This suggests that X 9 was significantly brighter during the Einstein observations than X 5 or X 7; inspection of Fig. 3 suggests that X 9 occasionally may indeed get bright enough to outshine X 5 and X 7.

3.2. Near the core; extended emission

Fig. 5 shows that there are four sources outside but near the core of 47 Tuc. The source density of the whole image is such, that these four sources all probably are members of 47 Tuc. In Fig. 5 we show the positions of the central sources of our HRI observations together with the two radio pulsars whose positions are known (to about $0.01''$): 47 Tuc C and 47 Tuc D (Robinson et al. 1995). Neither pulsar is detected in X-rays. No less than 11 radio pulsars have been detected in 47 Tuc; determination of the positions of pulsars 47 Tuc E to N is awaited to see whether any of them coincides with an X-ray source.

We investigate the existence of possible extended emission in two ways. First, we determine a total number of 3780 counts in a $100'' \times 100''$ region centered on the central sources, and then subtract the 3200 counts assigned by our multi-source fit to individually detected sources in this region. Of the excess of about 580 counts, some 230 are expected in the wings of the point spread functions of the individual sources, leaving about 350 counts. A similar excess is found by comparing the radial distribution of the detected counts with that of the point spread function between $20''$ and $60''$ from the X-ray center of the cluster. We conclude that there is extended emission in and/or near the core of 47 Tuc, with a countrate of ~ 6 cts/ksec, which corresponds to an X-ray luminosity at the distance of 47 Tuc of roughly $L_{0.5-2.5\mathrm{keV}} \sim 4 \times 10^{32}$erg/s. We cannot decide on the basis of our data whether this excess is due to one or two individual faint sources, or to a larger number of even fainter ones.

3.3. Sources not related to 47 Tuc

In the wider field of view shown in Fig. 1, we have optically identified just two sources. The identification of X 12 with HD 2072 in our view is fairly secure, for the reasons given in Paper 1: HD 2072 has visual magnitude $m_{\mathrm{V}} \simeq 9.1$, and the number of objects this bright in the optical is so small as to make chance coincidence unlikely. With $M_{\mathrm{V}} = 5.2$ for a G5 main-sequence star, we derive a distance of about 55 pc, and an X-ray luminosity for X 12 of $L_{0.5-2.5\mathrm{keV}} \sim 1.7 \times 10^{28}$erg/s, quite reasonable for a G 5 star. (The smaller distance and luminosity correct the values given in Paper 1.)

The identification of X 3 with a galaxy is somewhat less secure, in the sense that faint galaxies are sufficiently common to make a chance coincidence possible. Because the X-ray position of X 12 is more accurate than that of X 3, the shift between the optical and X-ray frame is determined mainly by the identification of X 12 with HD 2072, and thus is not affected much by the correctness of the identification of X 3 with the galaxy.

4. Discussion

We have detected five X-ray sources in the core of 47 Tuc, and noted possible optical identifications for three of them.

Before we discuss the possible nature of these sources, we adress the question how confident we can be about the identifications. To do this, consider an area of $20'' \times 20''$, centered on the cluster center according to Guhathakurta et al. (1992). From Fig. 2 we learn that this area contains three X-ray sources and 22 blue or variable stars. (Note that entry 8 of Table 3 in Geffert et al. (1997) almost coincides with AKO 6.) If we suggest identification for each blue object lying in a $4'' \times 4''$ box centered on an X-ray source, then the X-ray sources cover 12% of the search area, and we have 22 trials for probability 0.12. The probabilities of finding 0, 1, 2 or 3 identifications are 6, 18, 26 and 23 %, respectively. We conclude that the probability that all suggested identifications are accidential is quite high.

It may be argued that the suggested identifications are special also optically. If we consider the three objects V 1, V 2 and V 3 only, we have 3 trials for probability 0.12, and the probability of finding 0, 1 or 2 identifications are 68, 28 and 4 %. Even for this limited set, the probability that both identifications of V 1 with X 9 and V 2 with X 19 are due to chance is non-negligible. For the moment we conclude that our suggested identifications are possible, but not secure.

If we assume that V 1 and V 2 may be identified with X 9 and X 19, respectively, we learn from Fig. 4 that their ratio of X-ray to optical flux is rather high if they are cataclysmic variables, but as expected for soft X-ray transients in quiescence. The X-ray countrates of the cataclysmic variables in Fig. 4 have not been corrected for interstellar absorption; the correction is expected to be small for most systems, but not necessarily for all. For typical X-ray spectra of cataclysmic variables, the visual flux is affected more strongly by interstellar absorption than the X-ray countrate, and thus it is not expected that correction for absorption will increase the ratio of X-ray to optical flux for cataclysmic variables. We conclude that Fig. 4 provides another illustration of the argument originally made by Verbunt et al. (1984) that some of the dim X-ray sources in the cores of globular clusters are too bright to be cataclysmic variables.

The X-ray flux of X 9 is variable; that of X 19 may or may not be variable. The range of variability in X 9 is not unprecedented in soft X-ray transients in quiescence: the variations in the flux of Cen X-4 in quiescence, reported by Campana et al. (1997) and shown in Fig. 4, is of a similar magnitude as that observed in X 9. Such variations in a quiescent soft X-ray transient are not expected to be accompanied by detectable optical variations, and thus the absence of optical variation in V 1 need not be in conflict with the suggested identification. It may be noted that similar variations in the X-ray flux without accompanying variations in the optical are probably also possible in cataclysmic variables. For example, the dwarf nova VW Hyi was brighter in quiescence when observed with ROSAT in Nov 1990 than when observed with EXOSAT several years earlier (Wheatley et al. 1996, their Fig. 7).

V 2 has been detected at a level about 4 magnitudes above its quiescent level twice; this magnitude difference is more indicative of a dwarf nova than of a soft X-ray transient, as noted by Paresce & De Marchi (1994) and by Shara et al. (1996).

The two constant X-ray sources X 5 and X 7 in the core of 47 Tuc have no suggested optical counterparts. The level and the constancy of their X-ray fluxes are compatible with them being radio pulsars. For example, PSR B $1821-24$ in globular cluster M 28 and PSR J $0218+4232$, at comparable distances as 47 Tuc (5.5 and >5.7 kpc, respectively compared to 4.6 kpc for 47 Tuc), have ROSAT PSPC countrates of the same order of magnitude as X 5 and X 7. Whether X 5 or X 7, or any of the four X-ray sources just outside the core, can be identified with any of the 11 radio pulsars in 47 Tuc awaits further study of the radio pulsars, in particular determination of their positions, and of their period derivatives (so that the X-ray data can be folded on a known period). More accurate pinpointing of the X-ray positions will be possible with AXAF. Considering the large numbers of potential optical counterparts, optical or ultraviolet monitoring of the inner region of 47 Tuc simultaneous with the X-ray observations would be very useful, as detection of simultaneous X-ray and optical variability would strenghten any identification based on positional coincidence only.

To summarize, we find possible optical counterparts for three of the five X-ray sources in the core of 47 Tuc, but note that all could be chance positional coincidences. The X-ray luminosities of X 5, X 7 and X 9 are rather high for these to be cataclysmic variables, but compatible with soft X-ray transients in quiescence. X 9 is a variable X-ray source, and its X-ray to optical flux ratio suggests that it is a soft X-ray transient, hitherto always observed in quiescence. The steadier sources X 5 and X 7 may be either soft X-ray transients or recycled radio pulsars. The sources X 19 in the core, and X 4, X 6, X 11 and X 13, outside but near the core, have X-ray luminosities $L_{\rm X} < 10^{32}$erg/s, compatible with them being soft X-ray transients, cataclysmic variables, or recycled radio pulsars. If V 2 is indeed a cataclysmic variable, it is probably the best candidate counterpart hitherto suggested for an X-ray source in 47 Tuc.

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