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Astrometry of the globular cluster 47 Tucanae and possible optical identification of X-ray sources

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Abstract. Positions of stars of 47 Tuc have been derived by the use of photographic plates and CCD frames (ESO La Silla) and data from the Hubble Space Telescope (HST). The positions have been determined with respect to the PPM, which is based on the FK5 system. We have compared the positions of variable and blue stars in the core of 47 Tuc with those of the X-ray sources found by Hasinger et al. (1994). Taking into account a possible constant shift of the X-ray positions of up to 10″, there are three different solutions which would give identifications of four of the central X-ray sources with blue stragglers and variable stars. We discuss the nature of the X-ray sources and the different possible identifications. Since it is not possible to give a unique identification based on pure astrometric arguments, our positions may be taken for future identifications based on additional astrophysical arguments or coincident observations in different wavelengths. An identification of the X-ray source No. 3 of Hasinger et al. (1994) in the outer field of 47 Tuc with a galaxy was found.

Key words: astrometry – Galaxy: globular clusters: individual: 47 Tuc – X-rays: stars – blue stragglers

1. Introduction

The dynamical evolution of dense stellar systems like the cores of globular clusters may be significantly influenced by binaries (e.g. Hut 1996 and references therein). In a confrontation of theories with observations the detection of possible tracers of binaries like millisecond pulsars, X-ray binaries, cataclysmic variables, or blue stragglers plays an important role. One of the most promising objects for such a confrontation is the globular cluster 47 Tuc, where more than 40 blue stragglers (Paresce et al. 1991, Guhathakurta et al. 1992, De Marchi et al. 1993, Lauzeral 1993, Aurière et al. 1994), 11 millisecond pulsars (Manchester et al. 1991, Robinson et al. 1995), 2 cataclysmic variables (Paresce et al. 1992, Paresce & De Marchi, 1994) and 5 X-ray sources in the core (Hasinger et al. 1994), have been detected. In order to investigate the physical nature of these objects it is important to compare their stellar fluxes at different wavelength domains, which requires an optical identification of the objects detected in other wavelengths. Hasinger et al. (1994) have detected 15 X-ray sources in the field of 47 Tuc and discussed possible optical identifications of some of them. Of peculiar interest are the core sources which are expected to really belong to the cluster, whereas some of the external ones should belong to the field (Johnston et al. 1996).

X-ray globular cluster sources are classically divided in two classes (Hertz and Grindlay, 1983).

High luminosity ones are low-mass X-ray binaries (LMXB). Two of them were optically identified from the ground, in M15 (Aurière et al. 1984; Ilovaisky et al. 1993 and references herein) and in NGC 6712 (Nieto et al. 1990, Aurière & Koch-Miramond 1992) and confirmed by HST observations (Downes et al. 1996). A third one was resolved with the HST in NGC 6624 (King et al. 1993). Recently, Deutsch et al. (1996) presented an UV excess optical candidate for the luminous globular cluster X-ray source in NGC 1851.

Faint X-ray sources in globular clusters (so-called dim sources) are expected to be cataclysmic binaries. In a recent review Johnston et al. (1996) pointed out the various spectral properties of these objects. They concluded that this group of X-ray sources consists of different types of sources. At least in the globular cluster NGC 6397 Grindlay et al. (1995) conclusively identified three suspected optical counterparts (De Marchi & Paresce 1994, Cool et al. 1995) as magnetic cataclysmic variables. The case of the core of 47 Tuc is puzzling since the Einstein X-ray source was found to be too faint to be a LMXB and too bright to be a cataclysmic variable (Aurière et al. 1989). The discovery of several sources in the 47 Tuc core by ROSAT has not solved the problem since the sources are in the same intensity range (Hasinger et al. 1994). One of the best considered hypotheses is that these sources are transient LMXB in quies-

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cence (Bailyn, 1995), as first advocated by Verbunt et al. (1984). The basic problem in the identification process is to determine the link between the optical and the X-ray positions. Due to the crowding in the centre of 47 Tuc and due to a possible shift of the X-ray positions (Hasinger et al. 1994) the number of possible optical counterparts of the X-ray sources is high. In this paper we perform new astrometric measurements of the stars in 47 Tuc using groundbased (ESO La Silla) observations as well as HST data in order to look for the identifications of the X-ray sources in 47 Tuc.

2. Observations and reductions

The complete observational material used in this work is given in Table 1. Three steps were needed to link the rectangular HST positions to the PPM system (see Table 2). The first step was a determination of positions of 30 secondary reference stars around 47 Tuc by the use of photographic plates and 44 PPM stars. In a second step, positions of 2683 stars in a central field of $4' \times 4'$ of 47 Tuc were determined from CCD frames. In a third step we have transformed the rectangular coordinates of the stars from the HST observations from Guhathakurta et al. (1992) and De Marchi et al. (1993) into spherical ones. Standard procedures as described e.g. in Geffert et al. (1994) were used to measure and reduce the photographic plates and CCD frames. We obtained the root mean square (rms) of the deviations of our measurements from the PPM catalogue of 200 milliarcseconds (mas) in each coordinate. An intercomparison of the measurements of the two GPO plates yielded the rms of 150 mas.

DAOPHOT software (Stetson 1987) was used to determine the rectangular positions of the stars from the CCD frames. The rms of the deviations between the catalogue of the secondary stars and the rectangular positions on the CCD frames was 80 mas. These differences were mainly caused by the uncertainties of the secondary reference stars, since the deviations of x and y coordinates between the different CCD frames gave rms of 10 mas. For the reduction of the CCD-frames also third order polynomials of the rectangular coordinates x and y had to be taken into account. As seen in Table 2 the main uncertainty of our final positions is due to the determination of the positions with respect to the PPM system which amounts to 100 mas.

The transformation of the rectangular coordinates of De Marchi et al. (1993) and Guhathakurta et al. (1992) into spherical ones suffers from the problem that, due to the higher resolution, the HST-observations show several stars at the place of one star on the CCD frames. Because of these difficulties we have chosen a narrow search radius of 300 mas for the identification of the HST stars corresponding to our CCD based catalogue. Still we had the situation that in some cases more than one star from the HST observations corresponds to one of our catalogue stars. However, since we also excluded in the reduction stars having a positional deviation of more than 3σ, the accuracy of the transformation of the HST stars to our catalogue - as seen below - was sufficient. 120 stars remained in the reduction for the transformation from the rectangular HST coordinates of De Marchi et al. (1993) into spherical ones in our catalogue system. The rms of the deviations between the HST coordinates and our catalogue were 50 mas. The uncertainty of the transformation at the place of one star was better than 10 mas.

The situation is much worse with the positions of Guhathakurta et al. (1992). We derived a rms of 280 mas in each coordinate and a uncertainty of 100 mas at the place of one star. For stars in common with the catalogue of De Marchi et al. (1993) we took therefore preferentially the positions from their catalogue.

We made an astrometric catalogue of all candidates for beeing the optical counterparts of the X-ray sources in the core of 47 Tuc. Our catalogue contains positions of all known variable and blue stars (including the blue stragglers). Table 3 gives the cross-identifications and positions of these stars. We have taken mainly those positions which were determined from the measurements of De Marchi et al. (1993). For those stars which were located outside the field of De Marchi et al. (1993), we have taken preferentially the positions of Guhathakurta et al. (1992), then those of Lauzeral (1993) and Edmonds et al. (1996).

3. The X-ray positions in the field of 47 Tuc

Hasinger et al. (1994) list ROSAT X-ray positions from two observations in 1992 and 1993. While 15 sources were detected in the whole campaign, only 5 sources were visible in both observations. The small difference between the positions points to a constant offset of the ROSAT positions, as was the case in other observations (see remark in Hasinger et al. 1994 in chapter 3). Since the internal errors of the second observation are smaller than the errors from the first one, we have transformed all positions to the system of the second observation by using the five sources in common. The mean weighted deviations of the positions are (observation2−observation1) $-0\overset{s}{.}22 \pm 0\overset{s}{.}15$ seconds in right ascension and $-1\overset{''}{.}2 \pm 0\overset{''}{.}8$ in declination.

Since a constant offset of up to $5''$ for the ROSAT positions is possible (Hasinger et al. 1994), the number of possible candidates for an optical counterpart in a central part of a globular cluster is quite large. The optical identification of the X-ray sources in the central part is therefore not possible by a direct position to position comparison. In general the X-ray sources No. 7 and 9 are, with their small internal errors of the X-ray positions, the most promising candidates for a determination of the constant offset of the ROSAT positions.

One possibility for the determination of the constant offset of the ROSAT positions would be the use of the older Einstein X-ray position. As mentioned in Hasinger et al. (1994), the position of the X-ray source in 47 Tuc from the Einstein satellite (Grindlay et al. 1984) does not fit by its position to any of these sources detected by ROSAT. However, we learned from earlier investigations that the X-ray positions from the Einstein satellite may have an error of about $3''$ (Geffert et al. 1989, Geffert et al. 1994). The differences in position by the Einstein and ROSAT satellite may be also explained either by the constant positional

Table 1. The observations and their specifications

Date	Exposure time	NE	Telescope	Detector	Passband	Scale
Plates:						
1988-08-08	3,5 min	2	ESO/GPO	IIa-O	B	1mm=50″
CCD frames:						
1986-07-26	1,2 min	4	ESO/2.2m	GEC	U	1px=0.″26
1990-07-28	4,1,0.1 min	3	ESO/NTT	TEK	U,B,V	1px=0.″15
1990-07-29	5,1,0.2 min	3	ESO/NTT	TEK	U,B,V	1px=0.″15

NE = Number of plates/exposures

Table 2. The successive steps in our reduction

		Reference Stars	Reference Field	Target Stars	Target Field	Transform. Uncertainty
STEP I	Phot. Plates	44	$2^\circ \times 2^\circ$	30	$2'.6 \times 2'.6$	0.″08
STEP IIa	CCD frames	30	$2'.6 \times 2'.6$	2683	$2'.6 \times 2'.6$	0.″01
STEP IIIa	HST observations I	33	$2'.6 \times 2'.6$	57	$0'.7 \times 0'.7$	0.″10
STEP IIIb	HST observations II	120	$2'.6 \times 2'.6$	3567	$0'.3 \times 0'.3$	0.″01

HST observations I are from Guhathakurta et al. (1992)
HST observations II are from De Marchi et al. (1993)

shift of the ROSAT positions or by a possible variability of the X-ray source detected by the Einstein satellite. Taking into account that the position of the Einstein satellite is a mean of five pointings, one may assume that this position is the average of several sources, which were mixed and may have varied during the observations. Therefore we have not made use of the Einstein data in this paper.

4. Identification of X-ray sources outside the central region of 47 Tuc

In the following we will discuss the identification of the X-ray sources in the outer field of 47 Tuc. An identified X-ray source in the outer region of 47 Tuc would be important for the determination of the constant positional shift of the ROSAT positions.

4.1. Identification of source No. 3

All except one of the X-ray positions are located so close to the centre of 47 Tuc, that an identification on the ESO Quick Blue Survey copy is not possible due to crowding problems. Only the X-ray source 3 lies sufficiently to the outside to allow an optical identification. Given an error circle of about 10″ we found a faint galaxy on the ESO Survey at the place of the X-ray source No. 3. We have determined the optical position of the galaxy on two ESO GPO plates with respect to 44 PPM stars. A position of $\alpha_{2000} = 00^h 23^m 30^s.8$ and $\delta_{2000} = -72^\circ 20' 44''.0$ was obtained, which shows an offset of $-4''.2$ in α and $+1''.6$ in δ (in the sense ROSAT position minus ours). Although the image of the galaxy is quite faint on the GPO plates, the internal error is with $\pm 0''.4$ much smaller than the internal error of the ROSAT position, which amounts to $\pm 1''.7$.

4.2. Identification of source No. 12

The star HD 2072, which is according to Hasinger et al. (1994) the optical counterpart of source No. 12, is identical with the star 366 905 of the PPM catalogue. Since the PPM position is more precise than the position of the CDS used by Hasinger et al. (1994), we have taken the PPM position for the comparison with the ROSAT position. The position difference between the X-ray source No. 12 and HD 2072 is $+3''.2$ in α and $+1''.7$ in δ, which amounts to a total difference of $3''.3$.

Because the positional differences between X-ray and optical position of sources No. 3 and 12 are nearly in opposite directions it is impossible that both identifications are true. It is at this point impossible to judge which of the identifications is valid. Galaxies may be good X-ray source candidates but also the explanation of Hasinger et al. (1994) that HD 2072 as a late type star is an X-ray emitter seems plausible.

4.3. Identification of source No. 6

Hasinger et al. (1994) have suggested that X-ray source No. 6 could be identified with CPD −72 35B. However, the situation with CPD −72 35B is confusing. In the CPD star number −72 35 is designated as "neb.". The HD catalogue gives a cross

Table 3. Positions of variable and blue stars in the core of 47 Tuc. The epoch of the positions is 1988.

AKO	P	GYSB	DPF	L	E	V	α_{2000} [hhmmss.sss]	δ_{2000} [ddmmss.ss]
					13		002401.376	−720447.68
		32		942			002402.301	−720456.11
		84		1028			002402.996	−720519.61
					9		002403.262	−720426.69
					8		002403.448	−720504.61
	1	172	1596				002404.034	−720450.91
			2213			1	002404.286	−720457.68
		206		1200			002404.484	−720454.63
6	2		1984				002404.489	−720454.72
	3	253	2646				002404.886	−720501.67
9			2059		11		002404.946	−720455.13
				1273			002405.046	−720537.51
		241		1273			002405.086	−720537.49
					7		002405.244	−720451.11
		283		1328			002405.478	−720515.52
	4	302	1166	1334			002405.574	−720444.93
	5	299	1997		6		002405.578	−720453.67
	6		2772				002405.642	−720502.57
	7	312	2850				002405.700	−720503.76
	8		1953				002405.759	−720453.05
	9		2588				002405.946	−720459.94
	10		1582	1418			002405.990	−720448.67
						2	002406.017	−720455.85
	11		1581	1418			002406.052	−720448.60
	12		1757				002406.094	−720450.51
		381		1430	1		002406.372	−720437.05
		382		1447			002406.494	−720526.69
	13	386	2064				002406.414	−720453.68
	15	389	1030				002406.415	−720442.55
	14		1951				002406.446	−720452.30
	16		1286		12		002406.453	−720445.16
	17		1929				002406.507	−720452.01
	18	398	1758	1450	3		002406.532	−720450.04
		399		1456			002406.569	−720502.90
	21		1206				002407.710	−720442.98
					4		002407.822	−720458.07
		523		1628			002407.885	−720514.00
	19	534	2128				002407.925	−720452.73
					10		002407.942	−720501.64
	20		2732				002408.171	−720459.31
		572		5280			002408.573	−720430.76
		577					002408.653	−720510.28
					2		002409.070	−720504.87
		658		1826			002409.644	−720444.92
					5		002410.028	−720451.64
				2089			002412.135	−720445.68
		801					002412.253	−720446.67
		866					002413.587	−720445.66
		938					002415.794	−720441.24

AKO = Number in Aurière et al. (1989), P = Number im Paresce et al. (1991)
GYSB = Number in Guhathakurta et al. (1992), DPF = Number in De Marchi et al. (1993)
L = Number in Lauzeral (1993), E = Number in Edmonds et al. (1996)
V = Variable stars from Paresce et al. (1992) and Paresce & De Marchi (1994)

Table 4. A possible identification of the X-ray sources No. 5,7,8,9 from Hasinger et al. (1994). Also the positional deviations of the X-ray source No. 3 from the galaxy are given.

X-ray source	Optical counterpart	Δ_α [″]	Δ_δ [″]	$\sigma_{\rm X-ray}$ [″]
5	GYSB 32	−4.6	+0.4	±0.5
7	AKO 9	−4.6	+0.9	±0.2
8	GYSB 312	−5.6	−0.1	±1.5
9	DPF 2588	−6.0	+0.4	±0.2
Mean		−5.9	+0.4	
σ		±0.7	±0.4	
3	galaxy	−4.2	+1.6	±1.7

Δ_α = Pos. difference (ROSAT minus ours) in α
Δ_δ = Pos. difference (ROSAT minus ours) in δ
$\sigma_{\rm X-ray}$ = Int. error of the X-ray position
AKO = Number in Aurière et al. (1989)
GYSB = Number in Guhathakurta et al. (1992)
DPF = Number in De Marchi et al. (1993)
σ = Standard deviation of the differences

Table 5. Alternative identification of the X-ray sources No. 7,8,9,10 from Hasinger et al. (1994).

X-ray source	Optical counterpart	Δ_α [″]	Δ_δ [″]	$\sigma_{\rm X-ray}$ [″]
7	GYSB 172	−0.6	−3.3	±0.2
8	GYSB 253	−1.7	−2.2	±1.5
9	AKO 9	−1.6	−4.4	±0.2
10	DPF 1286	−0.7	−3.8	±2.8
Mean		−1.2	−3.4	
		±0.6	±0.9	

Δ_α = Pos. difference (ROSAT minus ours) in α
Δ_δ = Pos. difference (ROSAT minus ours) in δ
$\sigma_{\rm X-ray}$ = Int. error of the X-ray position
AKO = Number in Aurière et al. (1989)
GYSB = Number in Guhathakurta et al. (1992)
DPF = Number in De Marchi et al. (1993)
σ = Standard deviation of the differences

Table 6. A third possible identification of the X-ray sources No. 7,8,9,10 from Hasinger et al. (1994).

X-ray source	Optical counterpart	Δ_α [″]	Δ_δ [″]	$\sigma_{\rm X-ray}$ [″]
7	GYSB 241	−6.2	−3.1	±0.2
8	E7	−6.7	−4.0	±1.5
9	V2	−6.6	−3.7	±0.2
10	DPF 1206	−6.5	−6.0	±2.8
Mean		−6.5	+4.2	
		±0.2	±1.3	

Δ_α = Pos. difference (ROSAT minus ours) in α
Δ_δ = Pos. difference (ROSAT minus ours) in δ
$\sigma_{\rm X-ray}$ = Int. error of the X-ray position
GYSB = Number in Guhathakurta et al. (1992)
E = Number in Edmonds et al. (1996)
DPF = Number in De Marchi et al. (1993)
V2 = is the variable star from Paresce & De Marchi (1994)
σ = Standard deviation of the differences

identification of CPD −72 35 with HD 2051 but points out that star number HD 2051 is 47 Tuc. On the other hand the Southern Double Star Catalogue of Innes (1927) lists a double star with an angular separation of 6.21″ and a position angle of 251°, already found by Herschel. This double star is also in the Hipparcos Input catalogue with the number HIC 1902 (CCDM 00241−7206). Due to the uncertainty of the absolute position of Herschel, we believe that the identification of CPD −72 35 with Herschel's double star was a misidentification. Looking at our own CCD data we found the double star on our frames. The brighter component corresponds to the B8 III star already mentioned by Feast and Thackeray (1960) and which was found to be UV bright (de Boer & van Albada 1976, de Boer 1985). From our data we determined a position of α_{2000} = $00^h23^m58\overset{s}{.}23$ and δ_{2000} = $-72^\circ 05' 30\overset{''}{.}1$ and a separation of 6.57″ and a position angle of 247°.4 for this double star. Since this position is far away of any published X-ray position, we may rule out therefore an identification of the X-ray source No. 6 with any component of the double star.

5. On the identification of the X-ray sources in the core of 47 Tuc

In the following we look for an identification of the X-ray sources under the assumption, that most of the counterparts are objects from our Table 3. However we cannot rule out that the majority of the optical counterparts of X-ray sources may be too faint for our observations or look like normal stars. Taking into account a possible ROSAT shift of the X-ray position, we have looked for all objects from our Table 3 within a radius of 10″ of the X-ray source No. 7. The source No. 7 was chosen due to its small internal error and since the source was seen in both observational runs of Hasinger et al. (1994). 9 candidates from Table 3 were found. For each candidate, the difference between optical and X-ray position was used to shift the X-ray positions to the optical system. Then we looked in the error circle of each shifted X-ray position for objects from Table 3. Three possible solutions were found, by which 4 X-ray sources could be identified with candidates from Table 3, two solutions containing the most puzzling binary AKO 9 as a candidate.

5.1. Is AKO 9 an optical counterpart of one of the central X-ray sources?

AKO 9 is historically the candidate for the optical counterpart of the X-ray position from EINSTEIN observations (Aurière et al. 1989). It was found as the hottest resolved object in the error box for X0021.8-7221 during their 1986 July observations. Since then it has been shown to have faded by about 2 mag in U (Bailyn 1990a). AKO 9 could be identified with DPF 2059 on the ESO 2.2m observations, but was not visible on 1990 NTT observations, which confirms a 2 mag fading (Aurière et al 1994). Now, Meylan et al (1996), using the HST, observed it flaring, its UV brightness increasing by about 3 magnitudes in 2 hours. Edmonds et al. (1996) found AKO 9 (their variable 11) as an eclipsing binary. AKO 9 is thus a peculiar binary which could be an X-ray source. The position of AKO 9 is within 5 $''$ of the two ROSAT sources No. 7 amd No. 9 from Hasinger et al. (1994). The known properties of AKO 9 have been analysed by Minniti et al. (1996) who, however, could not derive its true nature since the observed flare in the UV has a unusual shape. The possibilities explored so far to explain the flare involve four types of objects (RS CVn, Cataclysmic Variable, soft-X-ray transient, nova) which are classically associated to X-ray sources which could be luminous enough to be detected with ROSAT at the distance of 47 Tuc.

Our first solution is presented in Table 4. This solution is in good agreement with the identification of the X-ray source No. 3 with the galaxy, as mentioned in chapter 4. Table 4 lists the identification and their $O - C$ data of this solution. The positional error of the ROSAT position of source 3 of $1\farcs7$ may explain the differences in column 3 and 4 between source 3 and the other sources.

On the other hand we arrive at an alternative solution taking into account the identification of AKO 9 with X-ray source No. 9. This would lead also to three other identifications of X-ray sources with blue stragglers. The same possibility was also taken into account by Meylan et al. (1996) and Minniti et al. (1996). The identifications with their differences between the X-ray and optical positions are given in Table 5. We wish to point out that both solutions are of identical value from astrometric point of view. Only the probable identifications of the X-ray source 3 would lead us to a preferred choice of the solution in Table 4. As to the solution in Table 5, the fact that X9 and AKO 9 are both transient objects with compatible positions is a favourable argument. It has to be noticed that AKO 9 could be associated with a ROSAT X-ray source even if it was not the case for any of the blue stragglers.

5.2. Variable stars as counterparts of the X-ray sources

Paresce et al. (1992) have proposed V1, a cataclysmic variable in the core of 47 Tuc, as the counterpart of one of the X-ray sources. V2, a dwarf nova, was discovered later (Paresce & De Marchi, 1994). V1 corresponds to DPF 2213 (Paresce et al. 1992) and V2 is located near to DPF 2184 (this follows from comparison of the data and charts of De Marchi et al. (1993) with the corresponding chart of Paresce & De Marchi, (1994)). Even when taking a possible shift of the ROSAT positions into account, it is not possible with the given relative positions of the identified objects to identify both variable stars together with any two ROSAT positions.

Recently Gilliland et al. (1995) and Edmonds et al. (1996) using HST observations have detected 13 variable stars in the central $66'' \times 66''$ region. Since their positions were given in the same system as those from Guhathakurta et al. (1992), we were able to determine the positions of the variable stars. Assuming a constant shift of the X-ray positions of Hasinger et al. (1994) can provide coincidences of optical and X-ray positions for only two objects, and then not unique ones but for several pairs of stars. Edmonds et al. (1996) are in favour of a solution which is in agreement with the identification of HD 2072 with the Source X12 from Hasinger et al. (1994). The astronomical data of their candidates give additional arguments for this solution. However, their identification of the variable 7 with the source X10 is astrometrically weak due to an error circle of $2\farcs8$ of the X-ray position. In addition, three of the central X-ray sources would then remain as not identified.

Taking blue stragglers and variable stars into account, we found an additional solution for the identification of four central X-ray sources with objects from Table 3. These identifications and their astrometric differences are presented in Table 6.

6. Discussion of the different solutions

The three solutions presented above could give for most of the X-ray sources in the core of 47 Tuc an optical counterpart. Moreover AKO 9, which is, due to its blue colour and variability, a very probable candidate of an X-ray source, is included in the identification. One solution is in agreement with the identification of one of the outer X-ray sources with a galaxy. This solution from Table 4 is our preferred solution. On the other hand, the fact that we have three nearly identical identifications, from astrometric point of view, for the central sources points to the fact that we have also superpositions by chance.

The solution of Edmonds et al. (1996) is compatible with transients in quiescence or magnetic cataclysmic variables. However, it concerns only two faint variable stars for which even the colour could not be measured. This also would imply that the non identified objects are very faint. Also, in this case, a larger number of possible identifications of one or two central X-ray sources exist. Nevertheless, one of the main interests of the solution of Edmonds et al. (1996) is to be compatible with HD 2072 being associated with X12.

ROSAT observed two blue stragglers in open clusters associated with X-ray sources: one in M67 and one in NGC 752 (Belloni & Verbunt, 1996). However, these are faint sources (around 10^{30} erg s^{-1}) and generally in 47 Tuc and other globular (and open) clusters we see many blue stragglers, which do not show X-ray emmission. Our question must therefore be, whether the optical counterparts of the X-ray sources in 47 Tuc may have the photometric characteristics of blue stragglers. This would imply that we are dealing with objects which by chance have similar photometric properties as classical blue stragglers. As presented in our introduction, the X-ray sources in the central field of 47 Tuc are puzzling since their X-ray luminosities are of an order of 1 magnitude higher than those of cataclysmic variables but much fainter than those of normal X-ray binaries. Hasinger et al. (1994) propose that these objects belong to the class of transient LMXBs in quiescence, similar to those objects in the galactic disk, which were found before by Verbunt et al. (1994). These objects are expected to appear very faint in the visible at the distance of 47 Tuc (Aurière et al 1989). One possibility in the present context could be that the 47 Tuc X-ray sources are active binaries as those discussed in Bailyn (1990b) and as could be AKO 9, which could mimic photometric properties of BSs. A safe identification will only be possible either by improvement of the absolute optical and X-ray positions or by coincident brightness variations in the optical and in the X-ray spectral range. In addition, it would be good to obtain spectra of the galaxy and of HD2072 in order to determine their nature and distance to test the hypothesis that one of them could be an X-ray source.

7. Search for optical counterparts of the millisecond pulsars in 47 Tuc

11 millisecond pulsars have been found in 47 Tuc but for only two, 47 Tuc C and 47 Tuc D, accurate radio positions (better than 100 mas) have been determined (Robinson et al. 1995). Unfortunately 47 Tuc C is located outside all of our CCD or HST fields. The position of pulsar 47 Tuc D is only within the field of our NTT observations. At the position of the pulsar we found a star with B=14.91 and $U-B$=0.32 at an offset of $1\farcs3$ and another star with B=18.08 and $U-B$=0.20 with an offset of $1\farcs4$ relative to the pulsar position. Since our positions are based on the PPM system, the positional differences of both stars from the radio position of the pulsar seem to be too large to propose an identification of one of these stars with the pulsar. However, a final decision will only be possible with the results of the Hipparcos mission.

8. Summary

We have determined optical positions of blue and variable stars in the centre of 47 Tuc with an internal accuracy of better than 100 mas. These data were used for a reinvestigation of the identification of the X-ray sources in 47 Tuc found by Hasinger et al. (1994). Under the assumption that the optical counterparts of the X-ray sources in 47 Tuc are stars from our Table 3, we present three solutions, which give optical counterparts of four central X-ray sources; one solution is in agreement with our proposition of identification of X-ray source No. 3, in the outer part of the cluster, with a galaxy.

Nevertheless, the solutions with blue stragglers as optical counterparts contain two problems. In the optical most of the candidates cannot be distinguished from classical blue stragglers, which are not generelly bright X-ray sources. In addition we cannot rule out that these identifications are only by chance. Advantages for our solutions are to give counterparts for four central sources and to include in two cases the most puzzling binary of the 47 Tuc core, AKO 9. If all of our solutions are wrong, then we may conclude that the majority of the true sources were too faint to be identified as blue or variable objects by the first HST observations.

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References

Aurière M., Le Fèvre O., Terzan A., 1984, A&A 138, 415
Aurière M., Koch-Miramond L., Ortolani S., 1989, A&A 214, 113
Aurière M., Koch-Miramond L., 1992, A&A 263, 82
Aurière M., C. Lauzeral, Koch-Miramond L., 1994, Hot stars in the core of 47 Tuc from NTT and HST observations. In: W. Wamsteker et al. (eds) Frontiers of Space and Ground-Based Astronomy, Kluwer Academic Publishers, p633.
Bailyn C., 1990a, in: C. Mauche (ed) Accretion powered compact binaries, Cambridge Univ. Press, 55
Bailyn C., 1990b, ApJ 357, L35
Bailyn C., 1995, Ann. Rev. of A&A 33, 133
Belloni T., Verbunt F., 1996, A&A 305, 806
Cool, A.M., Grindlay J.E., Cohn H.N., Lugger P.M., Slavin S.D., 1995, ApJ 439, 695
de Boer K.S., van Albada T.S., 1976, A&A 52, 59
de Boer K.S., 1985, A&A 142, 321
De Marchi G., Paresce F., Ferraro F.R., 1993, ApJS 85, 293
De Marchi G., Paresce F., 1994, A&A 281, L13
Deutsch E.W., Anderson S.F.,, Downes R.A., 1996, ApJ 472, L97
Downes R.A., Anderson S.F., Margon B., 1996, PASP 108, 688
Edmonds P.E., Gilliland R.L., Guhathakurta P., et al. , 1996, ApJ 468, 241
Feast M.W., Thackeray A.D., 1960, MNRAS 120, 463
Geffert M., Aurière M., Ilovaisky S., Terzan A., 1989, A&A 209, 423
Geffert M., Aurière M., Requième Y., Mazurier J.-M., 1994, A&A 282, 989
Gilliland R.L., Edmonds P.D., Petro L., Saha A., Shara M., 1995, ApJ. 447, 191
Grindlay J., Hertz P., Steiner J., Murray S., Lightman A., 1984, ApJ 282, L13
Grindlay J.E., Cool A.M., Callanan P.J., et al. , 1995, ApJ 455, L47
Guhathakurta P., Yanny B., Schneider D., Bahcall J., 1992, AJ 104, 1790
Hasinger G., Johnston, H.M., Verbunt, F., 1994, A&A 288, 466
Hertz P., Grindlay J., 1983, ApJ 275, 105
Hut P., 1996, Dynamics and binary (trans)formation in globular clusters. In: J. van Paradijs et al. , Compact stars in binaries, Proc. IAU Symp. 165, Kluwer Dordrecht, p. 377
Innes R.T.A., 1927, The Southern Double Star Catalogue, Johannesburg
Ilovaisky S., Aurière M., Koch-Miramond, L. et al, 1993, A&A 270, 139
Johnston H.M., Verbunt F., Hasinger G., Bunk W., 1996, ROSAT observations of globular clusters in the galaxy and in M31. In: J. van

Paradijs et al. (eds), Compact stars in binaries, Proc. IAU Symp. 165, Kluwer Dordrecht, p. 389
King I.R., Stanford S.A., Albrecht R. et al. , 1993, ApJ 413, L117
Lauzeral C., 1993, Ph.D. Thesis, University of Toulouse
Manchester R.N., Lyne A.G., Robinson C., et al. , 1991, Nature 352, 219
Meylan G., Minniti D., Pryor C. , Tinney C. G., Phinney E. S., Sams B., 1996, Proper motions with HST: searching for high velocity stars in the core of the globular cluster 47 Tuc: in ST-ECF/STScI second conference on Science with the HST, Paris, p. 316
Minniti D., Meylan G., Pryor C., Phinney E.S., Sams B., Tinney C.G., 1996, ApJ 474, L27
Nieto J.L., Aurière M., Sebag J., Arnaud J., Lelièvre G., Blazit A., Foy R., Bonaldo S., Thouvenot E., 1990, A&A 239, 155
Paresce F., Shara M., Meylan G., et al. , 1991, Nature 352, 297
Paresce F., De Marchi G., Ferraro F., 1992, Nature 360, 46
Paresce F., De Marchi G., 1994, ApJ 427, L33
Robinson C., Lyne A.G., Manchester R.N. et al. , 1995, MNRAS 274, 547
Stetson P.B., 1987, PASP 99, 191
Verbunt F., Belloni T., Johnston H.M., v.d. Klis M., Lewin W.H.G., 1994, A&A 285, 903
Verbunt F., van Paradjis, J., Elson, R., 1984, MNRAS 210, 899

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