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Letter to the Editor

Two new candidate ultra-compact X-ray binaries

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ABSTRACT

We present the identification of the optical counterparts to the low-mass X-ray binaries 1A 1246−588 and 4U 1812−12. We determine the X-ray position of 1A 1246−588 from *ROSAT*/PSPC observations and find within the error circle a blue star with $V = 19.45$, $B - V = 0.22$ and $R - I = 0.22$ which we identify as the counterpart. Within the *Chandra* error circle of 4U 1812−12, a single star is present which appears blue with respect to the stars in the vicinity. It has $R = 22.15$, $R - I = 1.53$. Distance estimates for both systems indicate that the optical counterparts are intrinsically faint, suggesting that they are ultra-compact X-ray binaries. These identifications would increase the number of candidate ultra-compact X-ray binaries from 2 to 4, whereas orbital periods are measured for only 7 systems in the Galactic disk.

Key words. X-rays: binaries – X-rays: individual: 1A 1246−588, 4U 1812−12

1. Introduction

The canonical low-mass X-ray binary consists of a neutron star or black hole and a low-mass main-sequence or (sub)giant donor star, and has an orbital period longer than one hour, up to several hundred days.

Recently, it has been found that the class of ultra-compact low-mass X-ray binaries makes up about half (5 out of 12) of the low-mass X-ray binaries in globular clusters (e.g., review by Verbunt & Lewin 2004), whereas a growing number of such systems is also discovered in the Galactic disk (7 with measured periods, and 2 candidates, see e.g., Juett & Chakrabarty 2003; Nelemans et al. 2004; Wang & Chakrabarty 2004). In addition, observations with the Wide Field Cameras (WFCs) of *BeppoSAX* have found a new class of low-mass X-ray binaries, bursters with (very) low persistent X-ray emission (Cocchi et al. 2001). The distribution of the sources in this class is more concentrated towards the Galactic center than that of the canonical low-mass X-ray binaries (Cornelisse et al. 2002).

To elucidate the evolutionary status and history of these systems, observations at longer wavelengths, in particular optical/infrared, are crucial. Such observations may reveal the orbital period, directly or indirectly (e.g., van Paradijs & McClintock 1994), or provide information about the donor and its chemical composition (e.g. Nelemans et al. 2004). The first step to such studies is the optical identification of the X-ray binary. In this letter we report two new optical identifications, which may be ultra-compact X-ray binaries.

2. X-ray observations

4U 1812−12 ($l = 18\overset{\circ}{.}03$, $b = 2\overset{\circ}{.}40$) has been observed by various X-ray satellites, but the observations with *BeppoSAX*/WFC and *Chandra* are most relevant for this paper. Type I X-ray bursts with photospheric radius expansion have been observed with the former, providing an unabsorbed bolometric peak flux of $(1.5 \pm 0.3) \times 10^{-7}$ erg cm^{-2} s^{-1} (Cocchi et al. 2000). A 1 ks observation with the back-illuminated S3 CCD aboard *Chandra* was analyzed by Wilson et al. (2003), yielding an accurate position of 4U 1812−12; $\alpha_{J2000} = 18^h15^m06\overset{s}{.}18$, $\delta_{J2000} = -12°05'47\overset{''}{.}1$, with an uncertainty limited by the *Chandra* boresight ($0\overset{''}{.}6$, 90% confidence; Aldcroft et al. 2000). A flux of 4.4×10^{-10} erg cm^{-2} s^{-1} (1–10 keV) and absorption of $N_H = (1.1 \pm 0.2) \times 10^{22}$ cm^{-2} were determined from spectral fits.

1A 1246−588 ($l = 302\overset{\circ}{.}70$, $b = 3\overset{\circ}{.}78$) has received much less attention, though it has been observed serendipitously by several X-ray observatories. A type I X-ray burst was observed with *BeppoSAX*/WFC (Piro et al. 1997) and a short (0.85 ks) follow-up observation with *ROSAT*/PSPC linked it to 1A 1246−588 (Boller et al. 1997). In this observation N_H was measured to be $(2.9 \pm 0.9) \times 10^{21}$ cm^{-2} and the 0.1–2.4 keV flux was 1.7×10^{-10} erg cm^{-2} s^{-1} (Boller et al. 1997). We have reanalyzed the *ROSAT*/PSPC observations of the field of 1A 1246−588 using standard routines from the EXSAS distribution (Zimmermann et al. 1996). In the 0.85 ks exposure obtained in February 1997, the X-ray binary is only 7′ off-axis, compared to 39′ in the much longer PSPC observation

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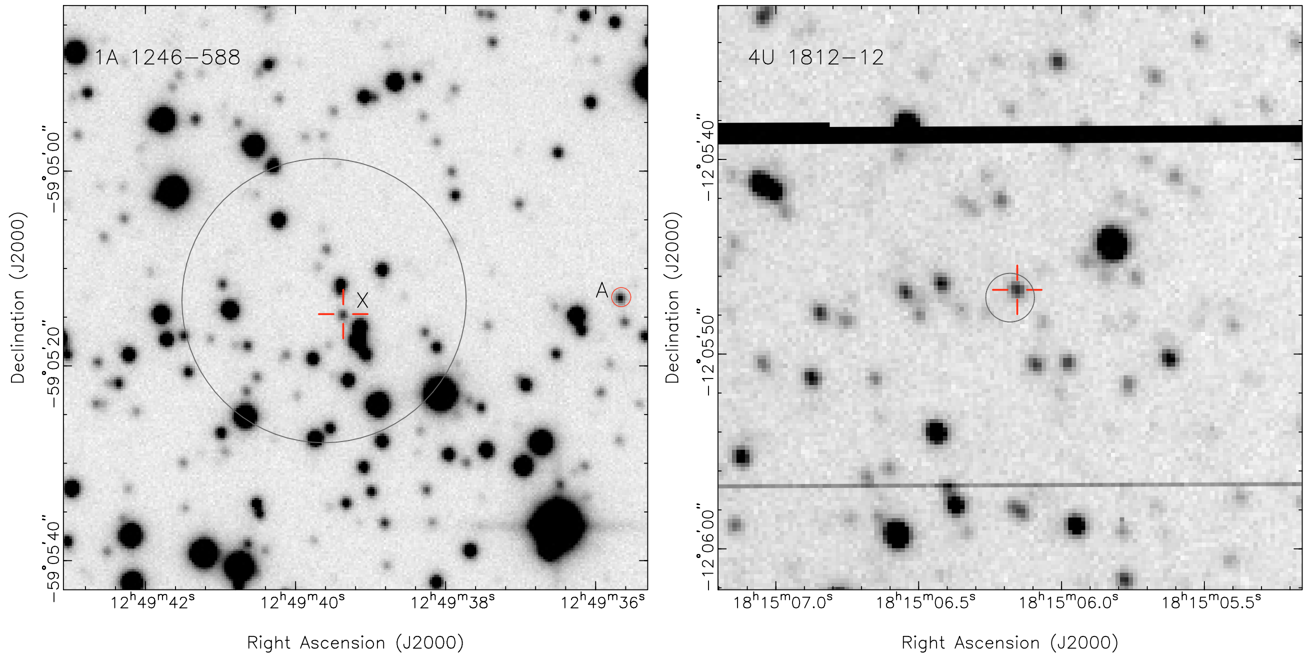

Fig. 1. *Left*: a 1′ × 1′ subsection of the combined 2 min *R*-band WFI image of 1A 1246−588. The 95% confidence error circle on the *ROSAT* position has a radius of 14.″6 and is depicted with the large circle. The proposed optical counterpart, star X, is indicated with the tick marks, while another blue star, star A, which is located outside the error circle, is encircled. *Right*: a 30″ × 30″ subsection of the 5 min *R*-band IMACS image of 4U 1812−12. The horizontal black bar in the top part of the image is a read out streak of a bright star, whereas the grey streak in the bottom part is a dead column of the CCD. The *Chandra* error circle (95% confidence, 1.″25 in radius) is depicted with the circle. The proposed optical counterpart is indicated with the tick marks.

from 1993, and the shorter observation provides the best source position. In this observation the X-ray binary has $\alpha_{J2000} = 12^h49^m39\overset{s}{.}61$, $\delta_{J2000} = -59°05'13\overset{''}{.}3$, with an internal uncertainty of 0.″3 on each coordinate. The external uncertainty on this position, the uncertainty in the bore-sight of the satellite, is about 6″ (Ayres 2004). Due to the short exposure only a few X-ray sources are present in the PSPC observation, and none of them are coincident with bright stars. Thus, no bore-sight correction is possible and the uncertainty on the position is dominated by the pointing uncertainty of *ROSAT*.

1A 1246−588 and 4U 1812−12 have been persistently detected in X-rays by the All Sky Monitor (ASM) onboard the Rossi X-ray Timing Explorer (RXTE). Both during, a few days before and a few days after the time of the optical observations described below both sources were detected at daily averaged count rates of at least 1 ASM count per second.

3. Optical observations

We retrieved archival observations of 1A 1246−588 obtained with the Wide Field Imager (WFI) at the ESO 2.2 m telescope on La Silla on March 26/27, 2000. A series of dithered 4 *B*, 6 *V*, 5 *R* and 5 *I*-band images were taken, all with exposure times of 2 min under clear conditions with 0.″8–1.″0 seeing. The field of 4U 1812−12 was imaged with the 6.5 m Inamori Magellan Areal Camera and Spectrograph (IMACS) at the Magellan Baade telescope on Las Campanas on July 6/7, 2005. A single 5 min image was obtained in both *R* and *I* under 0.″6 seeing. Both IMACS and WFI are mosaics of eight 4k × 2k detectors and we analyzed the images from the detector containing the X-ray binaries (chip 8 for 4U 1812−12 and chip 2 for 1A 1246−588). The WFI images have a pixel scale of 0.″24 pix^{-1}, while IMACS observations were taken with 2×2 binning, yielding a pixel scale of 0.″22 pix^{-1}. The science images were corrected for bias and flatfielded with domeflats using standard routines running within MIDAS.

Large-scale variations in the background of the *I*-band images, known as fringing, were present in the WFI observations. We corrected for this with a fringe frame. This fringe frame was constructed by median combining a set of 20 *I*-band images obtained earlier that night, such that it contained only the contributions of the sky and the fringe variations. The level of the sky was estimated and subtracted from this image, leaving only the fringe variations. This result was scaled to the fringe variations in the *I*-band images of the X-ray binary and subsequently subtracted from these images.

For the WFI observations, the images taken through the same filter were aligned using integer pixel offsets and median combined to remove image artifacts and increase the overall signal-to-noise ratio. Finally, a 4′ × 4′ subsection of the averaged images, centered on the nominal position of the X-ray binary, was extracted and used for the astrometry and photometry. For 4U 1812−12, a 3.′8 × 3.′8 subsection of the IMACS *R* and *I*-band images was extracted.

For the astrometry of the WFI observations of 1A 1246−588 we measured the centroids of all 31 astrometric standards from the second version of the USNO CCD Astrograph Catalog (UCAC2; Zacharias et al. 2004) that overlapped with the 4′ × 4′ subsection of the combined *R*-band image and that were not saturated and appeared stellar and

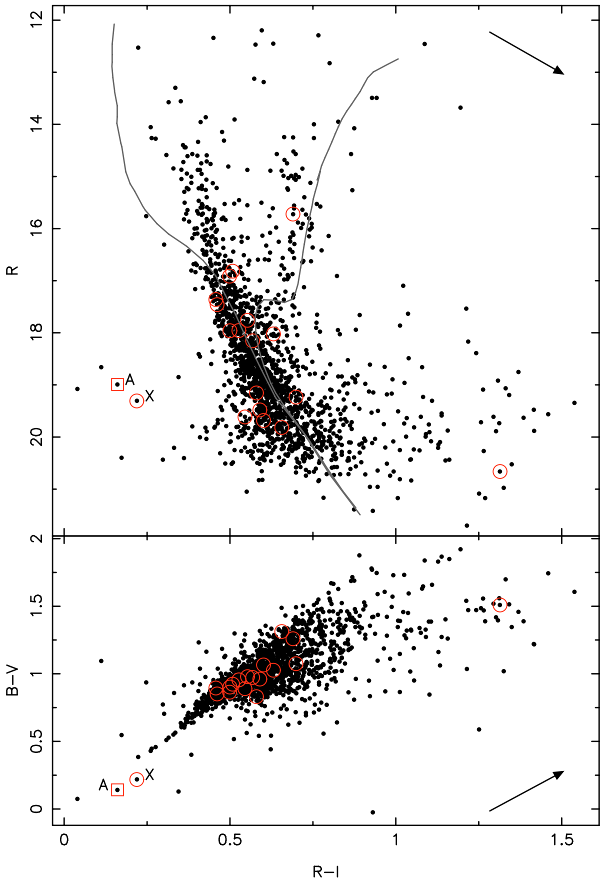

Fig. 2. *Top*: a colour–magnitude and colour–colour diagram (*bottom*) of the *BVRI* photometry of the 1A 1246−588 region. Stars inside the *ROSAT* error circle (Fig. 1) are encircled. Also shown in the CMD are two solar metallicity isochrones from Girardi et al. (2000), placed at a distance of 4.0 kpc and an absorption of $A_V = 1.0$. The left is for an age of 0.1 Gyr, while the right has an age of 10 Gyr. These isochrones are merely to guide the eye, as there will be a spread in distance, age, metallicity and absorption. The arrows indicate the effects of absorption, where the length of the arrow is for an extra absorption of $\Delta A_V = 1.0$. Of the stars present in the error circle, star X is exceptionally blue and the likely optical counterpart to 1A 1246−588. Star A has similar colours and magnitudes as star X, but is located outside the 95% confidence error circle.

unblended. We removed one outlier that had a total residual of $0\farcs74$, and the remaining stars were used to compute an astrometric solution, fitting for zero-point position, scale and position angle. The astrometric solution has root-mean-square (rms) residuals of $0\farcs054$ in right ascension and $0\farcs047$ in declination. We used a similar approach for the IMACS observations of 4U 1812−12, but had to use the USNO-B1 catalog (Monet et al. 2003) as very few UCAC2 standards overlapped with the IMACS images. About 70 USNO-B1 standards were used to calibrate a $3\farcm8 \times 3\farcm8$ subsection of the *R*-band image, giving a solution with rms residuals of $0\farcs19$ in right ascension and $0\farcs21$ in declination.

The DAOPHOT II package (Stetson 1987), running inside MIDAS, was used to determine instrumental magnitudes through point spread function (PSF) fitting. Aperture photometry of several bright stars was used to determine aperture corrections. For the calibration of the WFI observations we determined instrumental magnitudes of some 100 photometric standards in the standard field SA 98 and calibrated these against the calibrated values by Stetson (2000), fitting for zero-point and colour coefficients. We assumed extinction coefficients of 0.22, 0.19, 0.14 and 0.11 mag per airmass for *B*, *V*, *R* and *I*-band, respectively, taken from the WFI webpage[1]. The rms residuals of the calibration were 0.04 mag in *B* and *R*, 0.03 in *V* and 0.05 mag in *I*. The IMACS observations were calibrated using 11 standards in the T Phe field, again using values from Stetson (2000) and fitting for zero-point and colour coefficients. The standard field was imaged at similar airmass as the 4U 1812−12 field and no extinction coefficients were used. The rms residuals of the calibration were 0.05 mag in *R* and 0.07 mag in *I*.

In Fig. 1 we present finding charts for the regions of 1A 1246−588 and 4U 1812−12. We searched for optical counterparts to the X-ray sources in 95% confidence error circles on the *ROSAT* and *Chandra* position. For 4U 1812−12, a single star is located in the $1\farcs25$ error circle, while several stars lie inside the $14\farcs6$ error circle on the position of 1A 1246−588. We note that as both X-ray binaries are expected to have an accretion disk, the optical colours should display an excess of emission at blue wavelengths and thus appear blue, typically having $(B-V)_0 \approx 0.0$ (van Paradijs & McClintock 1995).

In Fig. 2 we show the colour–magnitude diagram (CMD) and a colour–colour diagram of the *BVRI* photometry of all stars on the $4' \times 4'$ image of 1A 1246−588. To illustrate the structure seen in the CMD, we have overplotted isochrones from Girardi et al. (2000). There are 3 stars that are exceptionally blue (having $B-V < 0.25$ and $R-I < 0.25$) and two of them, stars A and X, are near the error circle (Fig. 1). Star X has $V = 19.45 \pm 0.02$, $B-V = 0.22 \pm 0.03$, $V-R = 0.14 \pm 0.03$ and $R-I = 0.22 \pm 0.06$, while star A has $V = 18.99 \pm 0.01$, $B-V = 0.15 \pm 0.02$, $V-R = -0.01 \pm 0.02$ and $R-I = 0.16 \pm 0.04$. The mean colour and standard deviation of all stars in the 1A 1246−588 region is $B-V = 1.03 \pm 0.22$ and $R-I = 0.73 \pm 0.28$, and both star X and A are significantly bluer than this. Furthermore, at the observed *R*-band magnitude and $R-I$ colour, both stars are about half a magnitude bluer than the bulk of the stars at the same *R*-band magnitude. The optical position of star X is $\alpha_{J2000} = 12^h49^m39\fs364 \pm 0\farcs06$, $\delta_{J2000} = -59°05'14\farcs68 \pm 0\farcs05$, which is only $2\farcs4$ from the *ROSAT* position and well within the 1σ uncertainty of $6''$. Star A on the other hand has $\alpha_{J2000} = 12^h49^m35\fs660 \pm 0\farcs06$, $\delta_{J2000} = -59°05'12\farcs94 \pm 0\farcs05$, which is $30''$ (about 5σ) from the *ROSAT* position. We estimate that the probability of finding a star as blue as star X within the 95% confidence error circle of 1A 1246−588 is about 2%. Hence, we identify star X as the optical counterpart to 1A 1246−588.

A single star is present within the *Chandra* error circle of 4U 1812−12 at $\alpha_{J2000} = 18^h15^m06\fs155 \pm 0\farcs19$, $\delta_{J2000} = -12°05'46\farcs70 \pm 0\farcs21$. This position is only $0\farcs5$ from the X-ray position of 4U 1812−12 (Wilson et al. 2003). From the photometry we obtain $R = 22.15 \pm 0.02$ and

[1] `http://www.ls.eso.org/lasilla/sciops/2p2/E2p2M/WFI/zeropoints/`

$R - I = 1.53 \pm 0.03$. This star is not as blue as the counterpart of 1A 1246−588, however, in light of the larger absorbing column for 4U 1812−12, this is not surprising. Still, the counterpart is bluer than the bulk of the stars in the 4U 1812−12 region, which have $R - I = 1.88 \pm 0.23$. Furthermore, there are 9 stars within a radius of 5″ from the *Chandra* position of 4U 1812−12, and all, except the candidate counterpart, are redder than $R - I = 1.73$. Finally, we note that the probability of a chance coincidence of a star within the 95% confidence error circle is about 0.15%. We conclude that the star inside the error circle is the optical counterpart to 4U 1812−12.

4. Discussion

We have identified the optical companions to the low-mass X-ray binaries 1A 1246−588 and 4U 1812−12 based on their positional coincidence with the X-ray position and their colours. The counterpart to the first has $V = 19.45$, $B - V = 0.22$, while that of 4U 1812−12 is somewhat fainter at $R = 22.15$, $R - I = 1.53$.

Due to its position somewhat out of the Galactic plane, the hydrogen absorption column $N_{\rm H}$ towards 1A 1246−588 is moderate and suggests $A_{\rm V} = 1.7$ (Predehl & Schmitt 1995). This is smaller than the maximum absorption in this line-of-sight, which is predicted to reach $A_{\rm V} = 1.9$ around $d = 7$ kpc by the model of Drimmel et al. (2003). This limit constrains the absolute magnitude of the companion of 1A 1246−588 to $M_{\rm V} \gtrsim 3.5$. Though this reasoning assumes that both the model by Predehl & Schmitt (1995) and Drimmel et al. (2003) are correct, this distance is in agreement with estimates from *BeppoSAX*/WFC and RXTE/ASM observations of photospheric radius expansion bursts of 1A 1246−588, which suggest a distance of 5 kpc (in't Zand et al., in prep.).

For 4U 1812−12, the photospheric radius expansion bursts that have been observed by Cocchi et al. (2000) provide an estimate on the distance to this LMXB. Assuming an Eddington peak luminosity of $L_{\rm X} = 3.8 \times 10^{38}\,{\rm erg\,s^{-1}}$ for the accretion of helium-rich material (Kuulkers et al. 2003), the distance is estimated at 4.6 kpc. If hydrogen-rich material is accreted instead, the Eddington luminosity of $\sim 2 \times 10^{38}\,{\rm erg\,s^{-1}}$ reduces the distance to 3.4 kpc (see also Jonker & Nelemans 2004). Furthermore, the value of $N_{\rm H}$ derived from the X-ray absorption suggests $A_{\rm V} = 6.4$ (Predehl & Schmitt 1995) and, using the relative extinction coefficients of Schlegel et al. (1998), $A_{\rm R} = 5.2$. As such, the optical companion of 4U 1812−12 has an absolute R-band magnitude in the range of 3.6–4.2. If we assume that the counterpart has the same intrinsic colours as the counterpart of 1A 1246−588, which has $(V - R)_0 = -0.2$, this would translate to $M_{\rm V} = 3.4$−4.0.

These absolute magnitudes place both systems amongst the intrinsically fainter of the LMXBs known. According to van Paradijs & McClintock (1994), this suggests that these systems are ultra-compact X-ray binaries (UCXBs; having an orbital period below an hour). Here, the faintness of the counterpart is due to the reprocession of X-rays in a physically small accretion disk. However, these systems remain candidate UCXBs until the orbital period is determined, i.e. either through optical/IR or X-ray observations.

If these systems indeed turn out to have ultra-compact orbits, it is interesting to note that for the observed X-ray luminosities of $L_{\rm X} \approx 0.9 \times 10^{36}\,{\rm erg\,cm^{-2}\,s^{-1}}$ (1–10 keV) for 4U 1812−12 and $L_{\rm X} \lesssim 10^{36}\,{\rm erg\,cm^{-2}\,s^{-1}}$ (0.1–2.4 keV) for 1A 1246−588, these systems satisfy the notion presented by in't Zand et al. (2005); that LMXBs with persistent luminosities with $L_{\rm X} \lesssim 10^{36}\,{\rm erg\,cm^{-2}\,s^{-1}}$ may be ultra-compact X-ray binaries.

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