A LIKELY MICRO-QUASAR IN THE SHADOW OF M82 X-1

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ABSTRACT

The ultra-luminous X-ray source M82 X-1 is one of the most promising intermediate mass black hole candidates in the local universe based on its high X-ray luminosities (1039–1041 erg s−1) and quasi-periodic oscillations, and is possibly associated with a radio flare source. In this work, applying the sub-pixel technique to the 120 ks Chandra observation (ID: 10543) of M82 X-1, we split M82 X-1 into two sources separated by 1″. The secondary source is not detected in other M82 observations. The radio flare source is not found to associate with M82 X-1, but is instead associated with the nearby transient source S1 with an outburst luminosity of ~1039 erg s−1. With X-ray outburst and radio flare activities analogous to the recently discovered micro-quasar in M31, S1 is likely to be a micro-quasar hidden in the shadow of M82 X-1.

Key words: galaxies: individual(M82) – X-rays: binaries

1. INTRODUCTION

The ultra-luminous X-ray source (ULX) M82 X-1, with X-ray luminosities of ≥1039 erg s−1 and quasi-periodic oscillation (QPO) behavior, is one of the most promising intermediate mass black hole (IMBH) candidates in the local universe (Collura et al. 1994; Griffiths et al. 2000; Matsumoto et al. 2001; Strohmayer & Mushotzky 2003; Pasham et al. 2014). The discovery of an X-ray spectral state transition in M82 X-1 shows it has X-ray luminosities of LX ~ 1039 erg s−1 at the thermal-dominant state, suggesting an IMBH with mass ~200–800 M⊙ (Feng & Kaaret 2010). The discovery of the 60–120 mHz QPOs (Strohmayer & Mushotzky 2003; Fiorito & Titarchuk 2004; Mucciarelli et al. 2006; Caballero-García et al. 2013; Pasham & Strohmayer 2013) suggests the strong X-ray emission originates from the accretion disk instead of a jet, and suggests an IMBH of ~2 × 104 M⊙ if these low-frequency QPOs corresponds to the Keplerian frequency of the innermost stable orbit. Pasham et al. (2014) re-analyzed 6 yr RXTE X-ray observations and revealed the high-frequency, 3:2 ratio, twin-peak QPOs of 3.3 and 5 Hz, which, in combination with the low-frequency QPO revealed by an XMM-Newton observation, suggests an IMBH of 415 ± 63 M⊙ under the relativistic precession model.

Many efforts have been made to search for the radio counterpart of M82 X-1, and two radio sources were discovered at the vicinity of this ULX. A stable radio source 0″8 away from M82 X-1 is proposed to be a supernova remnant (SNR) and is not related to M82 X-1 (Collura et al. 1994; McDonald et al. 2002; Köring et al. 2005; Gendre et al. 2013). The other radio source was detected (at R. A. = 9:55:50.19, decl. = +69:40:46.0) throughout the 7 hr 1981 VLA observation at a 9 mJy flux level (Kronberg & Sramek 1985), but was not detected later in the 2003 VLA observations (Köring et al. 2005) or the 2005 VLA observations (Kaaret et al. 2006). Köring et al. (2005) re-examined the 1981 VLA data and found a 0″5 offset between the flare source and M82 X-1. Given the Chandra positional uncertainty of 0″6, it is not clear whether it is really associated with M82 X-1 and suggests relativistic beaming effects as the cause of the high X-ray luminosities. A careful work on astrometry is required to achieve a better understanding of M82 X-1.

In this paper, we re-analyze the Chandra ACIS observations with the sub-pixel technique to obtain improved spatial resolution and centroid accuracy. We describe our data analysis and results in Section 2 and discuss the implications of our work in Section 3.

2. DATA ANALYSIS AND RESULTS

2.1. Spatial Analysis

M82 X-1 has been observed 22 times by ACIS on board Chandra between 1999 and 2014, with off-axis angles from below 1″ to above 4″. The Obs IDs are: 361, 378, 379, 380, 1302, 2933, 5644, 6097, 6361, 8190, 10025, 10026, 10027, 10542, 10543, 10544, 10545, 10925, 11104, 11800, 13796, and 15616. In this work, we focus on Obs ID 10543 (PI: Strickland), which had the longest exposure of 120 ks with M82 X-1 placed only ~1″ from the aiming point. The energy range used in this paper is 0.3–8 keV unless stated otherwise. A careful examination of the Chandra image shows that the image size of M82 X-1 is larger than other nearby sources (e.g., J095551.2, see Figure 1), motivating our further analysis.

We reprocess the Level 1 event files using the chandra_rerepro command in the Chandra Interactive Analysis of Observations (CIAO, version 4.5) software. Following the standard pipeline, we remove time intervals with significant flares, as well as bad columns/pixels and events of bad grades, to produce the Level 2 event files. The check_xf_phi parameter was set to no to avoid the false removal of good events. The sub_pixel parameter was set to EDSER to enable sub-pixel analysis. Figure 1 shows the 1/8 pixel ACIS 0.3–8 keV image centered around M82 X-1 after reprocessing. Clearly, M82 X-1 is split into two fuzzy but discrete sources, while other nearby ULXs are not. Applying wavdetect to the image results in a detection of two sources, as presented in Table 1 and Figure 1. The brighter one is M82 X-1 itself, and its position (R.A. = 9:55:50.123, decl. = +69:40:46.54) is consistent with previously detected positions (e.g., Griffiths
et al. 2000). The second source (hereafter S1), with R. A. = 9:55:50.245 and decl. = +69:40:45.67, is located 1″ to the lower left of M82 X-1. Not detected by wavdetect is extra photon concentration to the lower right of X-1, which is probably caused by the point-spread function (PSF) feature like other nearby ULXs (e.g., see J095551.2 in Figure 1). In Obs ID 10543, M82 X-1 suffers from severe pile-up effects (see Section 2.2), which may affect its centroid. In comparison, the HRC observations do not suffer from pile-up effects and are expected to give accurate centroid positions for M82 X-1 and other sources. We have analyzed the HRC observations and listed the centroid positions for matched sources between the ACIS and HRC (Obs ID 8189) observations. As shown in Table 2, similar displacement of ~0″6 exists between the ACIS and HRC observations for all matched pairs, including X-1 despite the pile-up effects.

As Chandra’s PSF could be strongly distorted and cause a fake detection in the +Z direction (Chandra instrument layout directions are used in this paper for convenience)\(^4\), we need to ascertain whether they are real sources or just PSF artifacts.

The relative position of S1 strongly suggested S1 is a real source. The relative position of S1 to M82 X-1 in CCD is ~Y, which is different from the possible spurious source region (Figure 1, the cyan region centered at 15° counter clockwise to +Z) or the readout streak region (Figure 1). Moreover, the distance from X-1 to S1 is ~1″, greater than the PSF distortion region (~0″8), making it unlikely to be a PSF artifact. Indeed, none of other nearby bright sources show photon concentration in ~Y direction like S1, again supporting that S1 is a real source.

2.2. Spectral Analysis

The spectra and the respective rmf and arf files of M82 X-1 and S1 are extracted using specextract command in CIAO with

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\(^4\) See http://cxc.harvard.edu/cal/Hrc/PSF/acis_psf_2010oct.html and http://cxc.cfa.harvard.edu/ciao/caveats/psf_artifact.html for details.

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Figure 1. 1/8 pixel Chandra 0.3–8 keV image of M82 X-1. Solid black circles are 3σ error circles for detected sources as noted. Solid green circles, dashed green annulus, and the rectangle are for source and background spectra extraction. The Chandra instruments +Z and readout streak directions are given at the upper left corner. The cyan region shows the possible spurious source region caused by the PSF distortion. The “X” and the dashed black circle mark the radio flare position and its uncertainty brought by astrometry correction, respectively. The two sources, J095551.2 and J095550.6, marked with solid black circles at the lower-left corner are two nearby bright X-ray sources. Note that there are no count excess in the lower left direction of J095551.2.

Figure 2. Averaged 0.3–8 keV net count rates of S1 in Chandra ACIS observations between 1999 September to 2013 February. The 12 points from left to right refer to Obs ID 361, 1302, 2933, 5644, 6361, 10542, 10543, 10925, 10544, 11104, 13796, and 15616, respectively. The filled triangle corresponds to the detection of S1 in Obs ID 10543, and the open triangles are from observations without detection and should be treated as upper limits.
As shown above, S1’s spectrum is consistent with those in the low-hard states of black hole X-ray binaries (Remillard & McClintock 2006) and is intrinsically different from that of M82 X-1 or its readout streak at the 90% confidence level, again supporting that S1 is a real source.

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2.3. Temporal Behavior of S1

We further analyze other Chandra ACIS observations in a similar way as in Obs ID 10543. S1 is not detected in any other ACIS observations, including the three observations 10542, 10925, and 10544, observed about a week before and after Obs ID 10543, respectively. Using the same 0.3–8 keV extraction region and the same annular background region, we extract counts at S1’s position for all other ACIS observations. In Obs IDs 378, 379, 380, 6097, 8190, 10025, 10026, 10027, and 10545, S1 was fully buried in the PSF wings of X-1, so extraction results from these observations are excluded. In other observations, the PSF wing of M82 X-1 still partly cover S1 regions, and these obvious X-1 PSF wing regions are excluded. After this process, it is still possible that some photons in the extraction regions could come from X-1; thus the estimated count rates of S1 should be treated as upper limits. In Figure 2 we present the results. The 0.3–8 keV count rate of S1 was $\lesssim 0.001$ c/s in 1999 (Obs ID 361) and was $\lesssim 0.007$ c/s in 2009 (Obs ID 10542), then rose to $\sim 0.016$ c/s within a week (Obs ID 10543) and dropped to $\lesssim 0.0007$ c/s with seven days (Obs ID 10544). Judged from the light curve, S1 is likely a transient source in 0.3–8 keV band. This transient behavior, as well as the fact that S1 was usually in the shadow of M82 X-1’s PSF, is likely the reason why S1 was only detected once in 22 Chandra observations.

2.4. Astrometry

It is now possible to identify the radio flare source given the centroids of M82 X-1 and S1. Using three bright ACIS point sources ($\sigma > 60$; see Table 2 for details) with optical matches from the Sloan Digital Sky Survey (SDSS; Ahn 2014), we find a $0.4$ displacement between the ACIS coordinate frame and the SDSS coordinate frame (the same as the very long baseline interferometry coordinate frame with an error of $0.2$). The position of the radio flare source is corrected accordingly and registered to the ACIS image (Figure 1). The flare source is now 0.96 away from M82 X-1, but only 0.28 away from S1. Clearly, the position of M82 X-1 is no longer consistent with that of the radio flare source. On the other hand, S1’s position is consistent with the radio flare source within the positional uncertainty ($0.4$; mainly from the astrometric correction). If the radio flare is indeed associated with S1, it can be the radio outburst from a black hole X-ray binary when the binary transits from hard to soft states (e.g., Fender et al. 2004). Recently, Middleton (2013) discovered strong radio emission at a flux level $\lesssim 1$ mJy from a micro-quasar in M31 during its X-ray outburst at an X-ray luminosity of $1.3 \times 10^{39}$ erg s$^{-1}$. The properties of S1 are consistent with those of the M31 micro-quasar, and it can well be a similar micro-quasar, albeit with higher radio flux (9 mJy). However, unlike in the case of the M31 micro-quasar, the radio flare and the X-ray outburst for S1 were not detected simultaneously, and further simultaneous...
monitoring observations in radio and X-ray are needed to determine its exact nature.

3. DISCUSSION

M82 X-1, one of the most promising IMBH candidates in the local universe, is possibly associated with a radio flare source, suggestive of relativistic beaming effects for its extremely high X-ray luminosities. We have applied the sub-pixeling technique to the longest Chandra observation of M82 X-1, and split it into two separate discrete sources, namely X-1 itself and S1. Both relative positions and spectral properties show that S1 is a real source and not a PSF artifact, although it was detected only once out of 22 Chandra observations. Careful astrometric work shows that the radio flare source is associated with the transient S1. M82 X-1 is no longer associated with the radio flare, eliminating the necessity for relativistic beaming. The radio flare and X-ray outburst of S1 are analogous to those of a recently discovered micro-quasar in M31 (Middleton 2013), making it a likely micro-quasar in the shadow of M82 X-1.

The discovery of S1, however, does not affect previous results on M82 X-1’s spectral properties significantly (e.g., Feng & Kaaret 2010). This is because S1 luminosity, even in its outburst, is only $\sim 7 \times 10^{38}$ erg s$^{-1}$. In comparison, M82 X-1 exhibited X-ray luminosities from $2 \times 10^{40}$ to $\geq 10^{41}$ erg s$^{-1}$ (e.g., Kaaret et al. 2006; Feng & Kaaret 2010), 30–100 times higher than the outburst luminosity of S1. Furthermore, S1 was detected only once out of 22 Chandra observations between 1999 and 2014, and it must remain in a quiescent state at even lower luminosities most (>95%) of the time. However, S1 could become important for on-axis observations when M82 X-1 suffers severe pile-up. In the case of Obs ID 10543, the count rate of S1 is almost half of the observed count rate of M82 X-1.

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