

A high-velocity black hole on a Galactic-halo orbit in the solar neighborhood

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Only a few of the dozen or so stellar-mass black holes have been observed away from the plane of the Galaxy¹. Those few could have been ejected from the plane as a result of a “kick” received during a supernova explosion, or they could be remnants of the population of massive stars formed in the early stages of evolution of the Galaxy. Determining their orbital motion should help to distinguish between these options. Here we report the transverse motion (in the plane of the sky) for the black hole X-ray nova XTE J1118+480 (refs 2-5), from which we derive a large space velocity. This X-ray binary has an eccentric orbit around the Galactic Centre, like most objects in the halo of the Galaxy, such as ancient stars and globular clusters. The properties of the system suggest that its age is comparable to or greater than the age of the Galactic disk. Only an extraordinary “kick” from a supernova could have launched the black hole into an orbit like this from a birth place in the disk of the Galaxy.

The high galactic latitude ($l = 157.7^\circ$, $b = +62.3^\circ$) X-ray nova XTE J1118+480 was discovered² with the RXTE All-Sky Monitor on 2000 March 29. It exhibited slow outbursts that lasted ~ 7 months with a peak X-ray luminosity of 4×10^{35} (D/kpc)² erg s⁻¹ and energy spectra typical of black hole binaries in low/hard state⁶. From observations of the ~ 19 mag optical counterpart³ in quiescence a mass function for the compact object $f(M) \sim 6.0 \pm 0.4 M_\odot$ and an average distance of $\sim 1.85 \pm 0.36$ kpc were determined^{4,5}. For ~ 100 days the source exhibited a steady and slowly variable unresolved radio counterpart^{7,8} with persistent inverted radio spectrum, which is interpreted as optically thick emission from a compact, powerful synchrotron jet^{8,9}, that could have a size ≤ 0.03 AU⁹.

To measure the transverse motion on the plane of the sky of XTE J1118+480 we carried out observations of the radio counterpart with the Very Long Baseline Array (VLBA) at 15.4 GHz ($\lambda 2$ cm) and 8.4 GHz ($\lambda 3.6$ cm) on 2000 May 4 and July 24; afterwards it faded below detection. In both epochs the source was unresolved by the synthesized beams of 1×0.6 milli arc sec (mas) and 2×1 mas respectively, which correspond to physical dimensions smaller than ~ 0.7 D/kpc AU, and a brightness temperature $\geq 10^9$ K. Because of the high galactic latitude and low column of interstellar gas along the line of sight ($N_H \sim 10^{20}$ cm $^{-2}$)¹⁰, the VLBA images are relatively unaffected by Galactic electron scattering, allowing us to determine in each epoch the position of the compact, unresolved radio source with relative errors ≤ 0.35 mas.

The observations were done in cycles that included the target, the strong calibrator 3C273, a primary calibrator (Cal. 1) used as phase-reference source, and a second extragalactic calibrator (Cal.2). Their high elevation and good weather ensured that the phase connection was successful. The epoch, source, frequency, bandwidth, position, and flux for the VLBA observations of XTE J1118+480 and the two extragalactic sources used as references for relative astrometry are given in Table 1. The target had inverted and flat spectra, with similar fluxes within 10% of those interpolated from the monitoring with the Ryle⁷ and the Very Large Array telescopes¹¹, which confirms that the source was unresolved by the VLBA synthesized beams. Figure 1 shows a drift relative to the extragalactic frame between the two epochs of observation that after correction for parallax amounts to a proper motion on the plane of the sky of 18.3 ± 1.6 mas yr $^{-1}$ with position angle = $246^\circ \pm 6^\circ$.

To obtain a further assessment of the proper motion, we have performed an independent measurement in the optical using the photographic plates of the Palomar Observatory Sky Survey (POSS I & II), digitized for the Guide Star Catalogue-II project, which cover a time span of about 43 years. By relative astrometry we find that the secondary has a proper motion of 12.0 ± 3.2 mas yr $^{-1}$ with a PA = $240^\circ \pm 15^\circ$. Such a value is consistent both in magnitude and position angle with the more precise measurement obtained at radio wavelengths (see Figure 1).

The velocity components U, V, and W directed to the Galactic centre, rotation direction, and north Galactic pole are derived using the equations of transformation¹², and assuming the sun moves $(U_\odot, V_\odot, W_\odot) = (9, 12, 7)$ km s $^{-1}$ relative to the local standard of rest (lsr)¹³. For the reasons stated above, in the following we use the proper motion measured with the VLBA which after correction for change in parallax is: $\Delta\alpha = -16.8 \pm 1.6$ mas yr $^{-1}$ and $\Delta\delta = -7.4 \pm 1.6$ mas yr $^{-1}$. Distances of 1.8 ± 0.6 kpc⁴ and 1.9 ± 0.4 kpc⁵ are reported for XTE J1118+480, but for the radial velocity of the centre of mass somewhat discrepant values are estimated^{4,5}: $+26 \pm 17$ km s $^{-1}$ and -15 ± 10 km s $^{-1}$, respectively. For a mean value $d = 1.85 \pm 0.36$ kpc and $V_r = -15 \pm 10$ km s $^{-1}$, we find $(U = -97 \pm 23, V = -101 \pm 23, W = -39 \pm 12)$ km sec $^{-1}$ in the lsr frame. This implies that the source moves away from the Galactic centre, has slower rotation about the Galactic centre than the stars in the disk, and a 3σ motion towards the Galactic plane. Adopting $V_r = +26 \pm 17$ km s $^{-1}$, we obtain essentially similar results $(U = -114 \pm 24, V = -94 \pm 23, W = -2 \pm 17)$ km sec $^{-1}$, but with no significant motion perpendicular to the Galactic plane. Within the range of uncertainties for the distance (1.4-2.4 kpc) and radial velocity (-15 to +26 km s $^{-1}$), and irrespective of the specific values adopted, according to the definition of “high velocity star in the solar neighborhood” $-[(W+10) \geq 30$ km s $^{-1}$ and/or $(U^2 + V^2)^{1/2} \geq 65$ km s $^{-1}$]¹⁴– XTE J1118+480 can be considered a high velocity X-ray binary, since the velocity relative to the lsr is 145 km s $^{-1}$. The V component of XTE J1118+480 implies low rotation ($V_\phi \sim 122$ km s $^{-1}$) about the Galactic centre, contrary to the Galactic disk population, which in the solar neighborhood is in rapid rotation of ~ 220 km s $^{-1}$.

Figure 2 shows the orbit of the black hole binary about the Galactic centre derived from the mean values $(U = -105 \pm 16, V = -98 \pm 16, W = -21 \pm 10)$ km sec $^{-1}$ in the lsr frame, a distance of 1.85 ± 0.36 kpc from the Sun, and the standard galactic gravitational potential that includes the disk, bulge and halo components¹⁵. A change of 10% in any of the free parameters of the standard galactic gravitational potential¹⁵ results in changes of less than 5% in any of the orbital

parameters of XTE J1118+480.

We now discuss the possibility that XTE J1118+480 could have been launched from the Galactic plane into its halo orbit by a supernova explosion that took place during the formation of the black hole. Using the properties of XTE J1118+480^{4,5} ($M_{BH}=6.9\pm 0.9 M_{\odot}$, mass of the binary companion donor star $M_{donor}=0.3\pm 0.2 M_{\odot}$, binary separation of $3 R_{\odot}$ in circular orbit with orbital period of 0.17 days), and the equations that describe the impulse from symmetric explosions¹⁶, it is found that to accelerate the black hole up to a peculiar velocity of 217 km s^{-1} by a symmetric explosion more than $40 M_{\odot}$ would be suddenly ejected during the stellar collapse, which is implausibly large.

Alternatively, the supernova explosion could be asymmetric and the collapsar receive an additional kick that can be assumed to be equal for both black holes and neutron stars, the runaway velocity being proportional to the inverse of the mass¹⁷. Comparing with the runaway velocities of neutron stars, the momentum of XTE J1118+480 is similar to that of a solitary neutron star moving at 1000 km s^{-1} , ~ 10 times the average and ≥ 3 times the largest linear momentum among millisecond pulsars¹⁸. Therefore, an origin in the galactic disk would imply that XTE J1118+480 received the most extreme natal impulse among the known binaries that contain compact objects. Because binaries with more massive components are more likely to remain bound after the kicks¹⁷, and the binary orbit can circularize by tidal friction in few Myrs¹⁹, a disk origin through an extraordinary explosion cannot be ruled out.

Instead of being formed in the Galactic disk the black hole in XTE J1118+480 may be the relic of an ancient massive star formed in the Galactic halo. The values of U and V are consistent with the large random motions of old halo stars flying through the solar neighborhood²⁰ that have metallicities $[\text{Fe}/\text{H}] = -1.2$ to -1.4 . Furthermore, the Galactic orbit shown in Figure 2 is similar to that of some globular clusters (e.g. NGC 6656 with $[\text{Fe}/\text{H}] = -1.7$)²¹. We point out that there are two additional observations that are consistent with the hypothesis of a halo origin: 1) the very low metallicity $Z/Z_{\odot} \sim 0.1$ of the reflector medium derived from broad band X-ray spectroscopy²², and 2) the depletion of carbon and enhancement of nitrogen found in the ultraviolet spectrum with HST, which would require a long lasting Carbon-Nitrogen-Oxygen process, suggesting that the secondary lost a large fraction of its mass and is presently exposing the layers that were originally below the surface²³. Therefore, XTE J1118+480 may be contemporary of globular clusters, being one of the 10^4 - 10^5 black holes that were ejected from these old stellar systems²⁴ and at present swirl around in the halo.

In the year 2000 XTE J1118+480 brightened from quiescence by ~ 6 mag. Our analysis of the historical optical plates reveals that in the years 1995 and 1996 it had optical outbursts of ~ 2 mag that passed without notice, although could have been easily measured. We point out that XTE J1118+480 was a black hole nova with a remarkably large optical-to-X-ray flux ratio¹⁰ that reached a peak luminosity of about $10^{36} \text{ erg s}^{-1}$ in the 1-160 keV band⁶. Presently it is close to the Sun, but at the distance of the Galactic centre it would have not been detected in most surveys with X-ray instruments of large field of view. Therefore, it is possible that many faint X-ray binaries have been missed, which like XTE J1118+480 may sporadically appear as microquasars²⁵, namely as sources of collimated beams of relativistic particles and high energy photons. The association of these microquasars with a subset of unidentified gamma-ray sources²⁶ that are rather variable, soft, faint, and have -as globular clusters- a scale-height above the galactic plane of ~ 2 kpc, is an intriguing possibility.

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TABLE 1. VLBA astrometry of XTE J1118+480.

	Source	Freq (GHz)	BW (MHz)	RA(J2000) (h m s \pm mas)	DEC(J2000) (d ' " \pm mas)	Flux (mJy)
A	X1118	8.4	16	11 18 10.7918249 \pm 0.093	48 02 12.316177 \pm 0.131	5.9 \pm 0.3
A	Ref.2	8.4	16	11 26 57.6550573 \pm 0.014	45 16 06.284006 \pm 0.023	126 \pm 3.8
A	Ref.1	8.4	16	11 10 46.3458105 \pm 0.232	44 03 25.925163 \pm 0.240	264 \pm 5.3
A	X1118	15.4	32	11 18 10.7918131 \pm 0.084	48 02 12.316161 \pm 0.111	8.1 \pm 0.3
A	Ref.2	15.4	32	11 26 57.6550672 \pm 0.032	45 16 06.283518 \pm 0.050	68 \pm 2.0
A	Ref.1	15.4	32	11 10 46.3458105 \pm 0.232	44 03 25.925163 \pm 0.240	241 \pm 4.8
B	X1118	8.4	64	11 18 10.7914440 \pm 0.115	48 02 12.313919 \pm 0.155	2.7 \pm 0.1
B	Ref.2	8.4	64	11 26 57.6550224 \pm 0.008	45 16 06.283783 \pm 0.014	120 \pm 3.2
B	Ref.1	8.4	64	11 10 46.3458105 \pm 0.232	44 03 25.925163 \pm 0.240	267 \pm 5.2
B	X1118	15.4	64	11 18 10.7914531 \pm 0.159	48 02 12.314120 \pm 0.191	2.9 \pm 0.1
B	Ref.2	15.4	64	11 26 57.6550612 \pm 0.007	45 16 06.283338 \pm 0.014	65 \pm 1.8
B	Ref.1	15.4	64	11 10 46.3458105 \pm 0.232	44 03 25.925163 \pm 0.240	229 \pm 4.6

NOTES:

A = MJD 51668, 2000 May 04 UT 03:30-07:40; B = MJD 51749, 2000 July 24 UT 20:00-01:50. Between these two epochs the observed change in position of XTE J1118+480 with respect to the extragalactic frame, was Δ RA = -3.715 mas and Δ Dec = -2.149 mas. The positions at 8.4 and 15.4 GHz were averaged at each epoch and then differenced. The position of Ref.1 with associated absolute error is from the new catalog of VLBA calibrators (Personal Communication from D. Gordon, C. Ma, L. Petrov, A. Beasley, E. Fomalont & A. Peck, in preparation). The errors for other sources are formal fitting errors. The position of Ref.2 in this table agrees within 2σ with its absolute position from the new catalog. The systematic errors tend to cancel when the two epochs are differenced, and the residual errors in the relative astrometry are smaller than the short-term atmospheric “seeing” (fluctuations in position caused by residual tropospheric phase errors in the phase-referencing step). The correlator model used for both epochs was the same and contains a seasonally averaged global troposphere, but no short-term weather information. The phase referencing reduces the tropospheric errors to the measured level of 0.3 mas in each axis, as found by breaking the data into 1hr intervals and measuring the rms position scatter on the source ref.2. The errors for XTE J1118+480 are 0.35 mas in each axis, estimated by adding the (maximum) formal error of 0.2 mas in quadrature to the 0.3 mas tropospheric errors.

XTE J1118+480 proper motion

VLBA 2000 May 24 – Jul 24

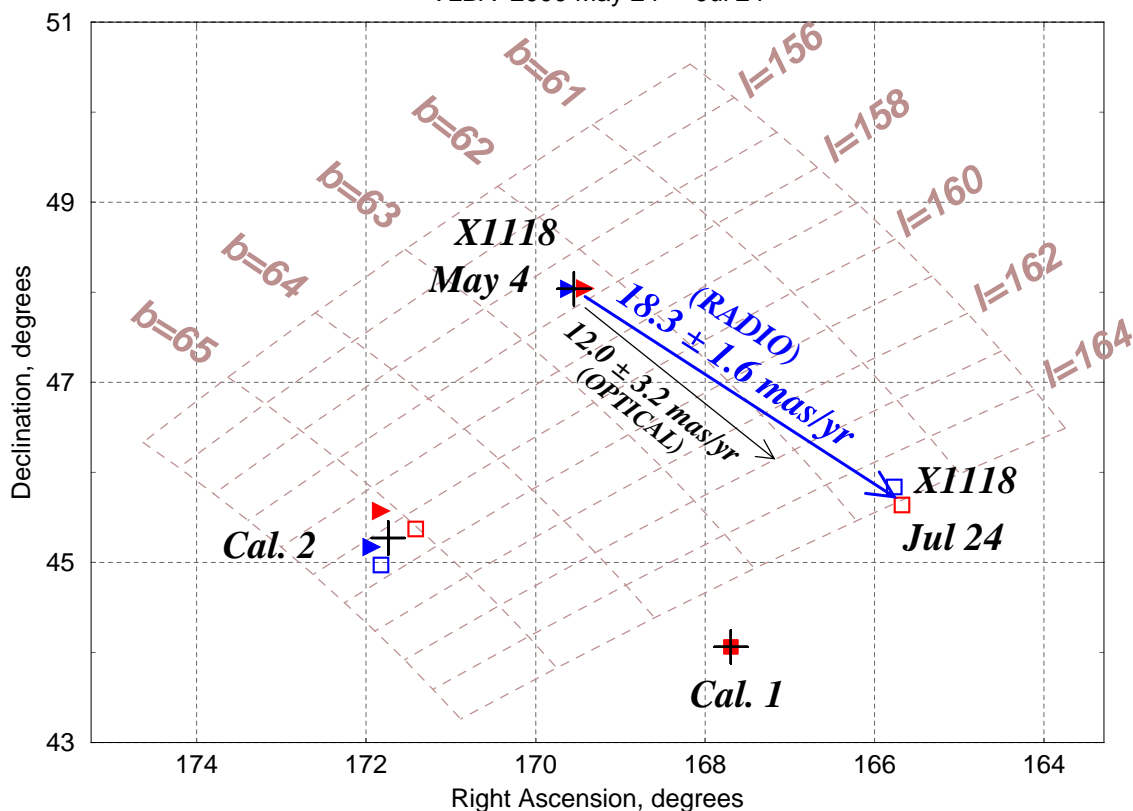


Figure 1: Proper motion of XTE J1118+480, observed with the VLBA on 4 May–24 July 2000. Shift in position (blue arrow) of the compact radio counterpart of XTE J1118+480 relative to the extragalactic background radio sources Cal. 1 and Cal. 2, measured at $\lambda 2\text{cm}$ (blue symbols) and $\lambda 3.6\text{cm}$ (red symbols) on 2000 May 4 (triangles) and 2000 July 24 (squares). The black crosses mark the mean positions. For clarity, the J2000 equatorial coordinates (black lines) and galactic coordinates (dashed brown lines) are shown in expanded scales of 2° and 1° per division respectively. The position of Ref 1, the primary reference source is identical at both wavelengths and both epochs, by definition. The position of Ref. 2 is the same at all wavelengths and epochs, within rms ~ 0.35 mas. To relate the astrometric positions of XTE J1118+480 in Table 1 to the galactic frame, a correction for the change in parallax was applied. The position of XTE J1118+480 shifts by -16.8 ± 1.6 mas yr $^{-1}$ in right ascension and -7.4 ± 1.6 mas yr $^{-1}$ in declination at both wavelengths. The thin black arrow shows the proper motion of the optical companion measured from a set of four photographic plates that cover a time span of ~ 43 years (from 1953 to 1996). A linear fit to the object positions yielded a proper motion of -10.5 ± 3.2 mas yr $^{-1}$ in right ascension and of -5.9 ± 3.2 mas yr $^{-1}$ in declination, after correcting for the galactic rotation and for the peculiar motion of the Sun. The difference in position angle between the radio and optical is 6° , and the errors $\pm 5^\circ$ and $\pm 15^\circ$, respectively.

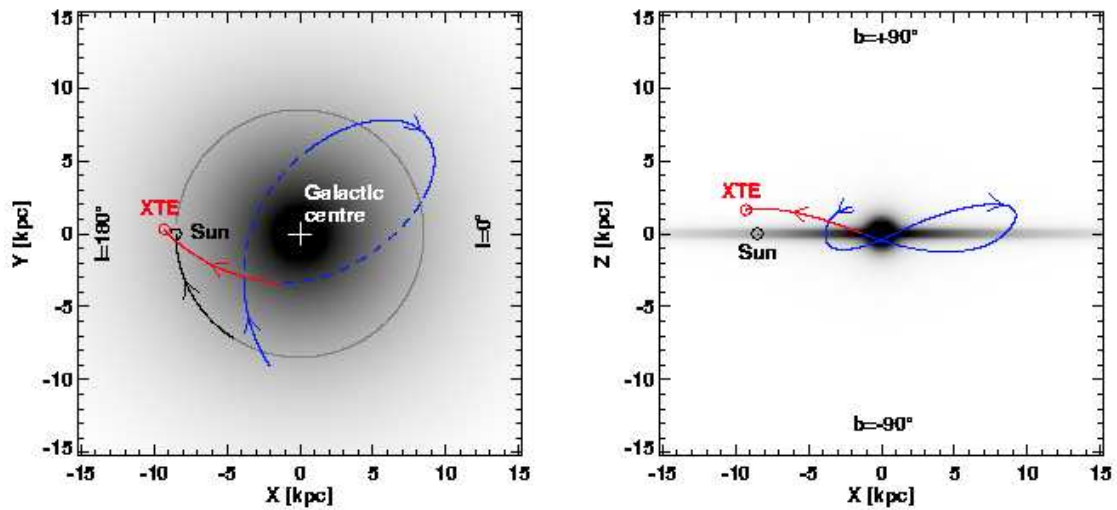


Figure 2: Galactic orbit of XTE J1118+480 during the last orbital period of the Sun around the Galactic centre (240 Myr). The mid-plane mass density distribution of the Galactic bulge and disk are represented by a linear grey scale. The last section of the orbit since the source left the plane 37.3 ± 4.8 Myr ago at a galactocentric distance of 3.8 ± 0.5 kpc is in red color. The trajectory of the Sun during the later time is indicated by the thick black arc. The source left the plane towards the Northern Galactic Hemisphere with a galactocentric velocity of 348 ± 18 km s⁻¹, which after subtraction of the velocity vector due to galactic rotation, corresponds to a peculiar space velocity of 217 ± 18 km s⁻¹ relative to the galactic disk frame, and a component perpendicular to the plane of 126 ± 18 km s⁻¹. The orbit of XTE J1118+480 has an eccentricity $e=0.54$ and is similar to the orbits of halo objects, such as globular clusters. In the oscillating motion about the plane it has just turn around to fall back in. At the present epoch XTE J1118+480 is at a distance from the Sun of only 1.85 ± 0.36 kpc flying through the Galactic local neighborhood with a velocity of 145 km s⁻¹. **Left:** View from above the Galactic plane; **Right:** side view