A Black Hole Kicked at Birth: MAXI J1305-704

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Abstract

When a compact object is formed in a binary, any mass lost during core collapse will impart a kick on the binary’s center of mass. Asymmetries in this mass loss or neutrino emission would impart an additional natal kick on the remnant black hole or neutron star, whether it was formed in a binary or in isolation. While it is well established that neutron stars receive natal kicks upon formation, it is unclear whether black holes do as well. Here, we consider the low-mass X-ray binary MAXI J1305-704, which has been reported to have a space velocity $\geq 200$ km s$^{-1}$. In addition to integrating its trajectory to infer its velocity upon formation of its black hole, we account for recent estimates of its period, black hole mass, mass ratio, and donor effective temperature from photometric and spectroscopic observations. We find that if MAXI J1305-704 formed via isolated binary evolution in the thick Galactic disk, then the supernova that formed its black hole imparted a natal kick of at least 70 km s$^{-1}$ while ejecting less than $\approx 1 M_\odot$ with 95% confidence assuming uninformative priors on mass loss and natal kick velocity.

Unified Astronomy Thesaurus concepts: Astrophysical black holes (98); Low-mass x-ray binary stars (939); Supernovae (1668)

1. Introduction

The physics underlying supernovae (SNe) and explosive mass loss may be imprinted on the velocities of the compact objects they leave behind. While any sudden mass lost from a component of a binary system will impart a velocity on the objects they leave behind. While any sudden mass lost from a component of a binary system will impart a velocity on the objects they leave behind, whether it was formed in a binary or in isolation. While it is well established that neutron stars receive natal kicks upon formation, it is unclear whether black holes do as well. Here, we consider the low-mass X-ray binary MAXI J1305-704, which has been reported to have a space velocity $\geq 200$ km s$^{-1}$. In addition to integrating its trajectory to infer its velocity upon formation of its black hole, we account for recent estimates of its period, black hole mass, mass ratio, and donor effective temperature from photometric and spectroscopic observations. We find that if MAXI J1305-704 formed via isolated binary evolution in the thick Galactic disk, then the supernova that formed its black hole imparted a natal kick of at least 70 km s$^{-1}$ while ejecting less than $\approx 1 M_\odot$ with 95% confidence assuming uninformative priors on mass loss and natal kick velocity.

Other studies have turned to X-ray binaries (XRBs) with BH accretors—aided by the growing subset of systems with known proper motions and radial velocities—to constrain natal BH kicks. Some used just these kinematic constraints to estimate birth velocities of known XRBs, suggesting that they may have received kicks in excess of what they could have received due to symmetric mass loss alone (Mirabel et al. 2001; Repetto et al. 2012; Atri et al. 2019; Sánchez et al. 2021). Others combined the kinematic constraints with observational constraints on the orbital, BH, and donor properties, modeling the binary evolution and core collapse of their XRB progenitors to individually constrain mass loss and natal kicks (Willems et al. 2005; Fragos et al. 2009; Wong et al. 2012, 2014). Of these studies that considered both kinematic and binary/stellar observational constraints, most found only upper limits on the BH natal kicks with one exception: XTE J1118+40, which Fragos et al. (2009) found must have received a natal kick in excess of $\approx 80$ km s$^{-1}$. Here, we focus on the case of the low-mass X-ray binary (LMXB) MAXI J1305-704 because of its high peculiar velocity ($V_{pec} \approx 80^{+30}_{-30}$ km s$^{-1}$), distance above the Galactic plane ($|Z| \approx 1$ kpc), and short orbital period ($P \approx 0.4$ days), reported in Sánchez et al. (2021). We constrain both its evolutionary and kinematic history to find a lower limit on its BH natal kick, making it only the second fully modeled BH system that must have received a natal kick at birth.

While BH LMXBs may form dynamically via binary exchanges or single-single captures (Clark 1975; Hills 1976), here we work under the assumption that MAXI J1305-704 (hereafter J1305) formed in the Galactic field and evolved as an isolated binary. The standard isolated formation channel for BH
2. MAXI J1305-704

While there are hundreds of known XRB sources, only about two dozen have confirmed BH accretors. Of these, 21 are classified as LMXBs (Jonker et al. 2021), having companions less than a few solar masses. There are proper motion measurements in the literature for 16 of these, and only 12 are complete with radial velocity measurements (Atri et al. 2019), crucial to estimating peculiar velocities and inferring BH kicks. Of these systems, J1305 is particularly interesting because of its high distance above the Galactic plane, with \( |Z| \approx 1 \text{ kpc} \), and low orbital period (\( \approx 0.4 \) days), which is particularly helpful in constraining its progenitor properties (see Section 3.2 for details). J1305 was first discovered by the International Space Station’s Monitor of All-sky X-ray Image instrument (Matsuoka et al. 2009; Mihara et al. 2011) and was first identified as an X-ray transient in Sato et al. (2012). Follow-up observations classified J1305 as an LMXB, potentially accreting onto a stellar-mass BH (Greiner et al. 2012; Kennea et al. 2012; Suwa et al. 2012; Morihana et al. 2013). The nature of its accretor was confirmed by Sánchez et al. (2021), after photometric and spectroscopic observations of J1305 in quiescence. They found that J1305 has an orbital period of \( 0.394 \pm 0.004 \) days, consisting of a BH of mass \( M_{\text{BH}} \approx 8.9_{-1.6}^{+1.0} M_\odot \). With an observed mass ratio \( q_{\text{obs}} = 0.05_{-0.02}^{+0.02} \) and donor effective temperature \( T_{\text{eff,obs}} = 4610_{-160}^{+130} \text{ K} \), they find that the companion is an evolved dwarf star with \( M_{\text{star,obs}} = 0.43_{-0.16}^{+0.16} M_\odot \) and an effective temperature of \( T_{\text{eff}} = 4610_{-160}^{+130} \text{ K} \). They estimated that J1305 is at a distance of \( d = 7.5_{-1.4}^{+2.8} \) kpc, with a radial velocity of \( v_r = 9.5_{-2.3}^{+2.5} \text{ km s}^{-1} \). Combining this with proper motion measurements in the direction of R.A. and decl. (\( \alpha \) and \( \delta \), respectively) from GAIA (Gaia Collaboration et al. 2021) of \( \Delta \alpha \cos \delta = -7.89_{-0.62}^{+0.62} \text{ mas yr}^{-1} \) and \( \Delta \delta = -0.16_{-0.72}^{+0.72} \text{ mas yr}^{-1} \), they calculated a peculiar velocity with respect to the local Galactic rotation of \( V_{\text{pec}} = 80_{-30}^{+30} \text{ km s}^{-1} \). While we cannot exclude that J1305 originated in a globular cluster, this suggests that if it indeed originated in the thick disk, then J1305 may have received a natal kick at birth.

3. Constraining the Progenitor of J1305

We mostly follow the methodology described in Wong et al. (2014), using kinematic modeling to infer the potential peculiar velocities of J1305 at the birth of its BH, and then constrain the possible pre- and post-SN binary properties using forward modeling to extract the asymmetric natal kick on the BH from the total imparted peculiar velocity inferred kinematically. However, rather than use a rapid population synthesis code based on fits to single-star models when evolving potential progenitors, we compute detailed binary stellar evolution sequences using MESA and generate populations with POSYDON (Fragos et al. 2023), which is trained on MESA binary evolution grids and fully consistent with its treatment of binary stellar evolution and MT. Except for where otherwise noted in relation to our treatment of core collapse, all of our parameter choices and prescriptions are as described in POSYDON v1.

3.1. Kinematics

We begin by using the observed proper motion of J1305 to constrain the total velocity imparted by the SN upon the birth of its BH. Following the methodology of Wong et al. (2014), we assume that J1305 formed in the Galactic disk and integrate
its trajectory backwards to infer the systemic velocity of J1305 upon the birth of its BH \(V_{\text{pec,birth,obs}}\). In Section 3.2, we infer the possible range of pre- and post-SN properties of the binary to extract the range of natal kicks required to create this birth velocity.

We model the Milky Way with the static potential of Carlberg & Innanen (1987) and updated parameters from Kuijken & Gilmore (1989). We start with a coordinate system with axes XYZ with origin at the Galactic center, where \(Z=0\) coincides with the Galactic midplane, the positive Y-axis is in the direction of Galactic rotation at the location of the Sun, and the negative X-axis connects the projection of the Sun onto the Galactic midplane to the Galactic center. Assuming a distance from the Sun to the Galactic center of \(R_0=8.05\) kpc and local rotational velocity of \(v_0=238\) km s\(^{-1}\) (Honma et al. 2012), this places the Sun at \((X_0, Y_0, Z_0) = (-8.05, 0, .03)\) kpc with a velocity of \((U_0, V_0, W_0) = (11.1, 12.24, 7.25)\) km s\(^{-1}\) with respect to the local standard of rest. Meanwhile, adopting the distance to J1305 of \(d=7.5^{+2.5}_{-1.4}\) kpc from the analysis in Sánchez et al. (2021), this puts J1305 at \((X, Y, Z) = (-3.87, -6.15, -0.98)\) kpc. Combining this with the radial velocity \(\gamma=9^{+5}_{-3}\) km s\(^{-1}\) from that analysis with the angular velocity measurements \((\Delta \Omega, \Delta \delta) = (-7.89^{+6.62}_{-0.62}, -0.16^{+0.72}_{-0.72})\) mas yr\(^{-1}\) from the GAIA Early Data Release 3 (Gaia Collaboration et al. 2021), we compute the proper motion of J1305 with respect to our local standard of rest, finding \((U, V, W) = (-227, -140, 20)\) km s\(^{-1}\).

In order to estimate J1305’s peculiar velocity upon the birth of its BH, we integrate its trajectory backwards in time and sample potential peculiar velocities at moments that coincide with crossings of the Galactic midplane within 10 Myr of the age of a donor star from the winning RLO2 sequences. We take the donor age as a proxy for BH age under the assumption that the lifetime of the BH progenitor is negligible with respect to the age of our winning donors. We plot the result in Figure 1, finding that J1305 likely had a peculiar velocity of \(V_{\text{pec,birth,obs}} = 74^{+7}_{-6}\) km s\(^{-1}\) just after the birth of its BH, and treat this as an observable. Assuming that prior to the core collapse of its primary, J1305 was moving in the Galactic midplane with the local Galactic rotation, this gives a measure of the total velocity imparted on J1305’s center of mass upon core collapse. This assumption that J1305 was born directly in the disk at \(Z=0\) kpc with exactly the circular velocity at that location equates to assuming a “kinematically cold” disk. To check that our results are not affected by this assumption, we compared J1305’s current peculiar velocity to that obtained when using the average velocities of systems nearby J1305’s projection onto the Galactic midplane using GAIA (Gaia Collaboration et al. 2021) and find no significant quantitative difference. We also reran the analysis using gaia’s MilkyWayPotential (Bovy 2015; Price-Whelan 2017; Price-Whelan et al. 2020) and found that our results are not significantly affected by our particular choice of Galactic potential.

3.2. Binary Evolution

We now use the possible pre- and post-SN parameter space of J1305’s progenitor in order to extract the BH natal kick from the total imparted systemic velocity inferred from its kinematics. We do this in two steps: First we constrain the BH mass, donor mass, and period \((M_{1,\text{RLO2}}, M_{2,\text{RLO2}}, P_{\text{RLO2}})\) at

Figure 1. Here we plot the possible kinematic histories of J1305. In blue we plot the trajectory corresponding to taking the median observed position and proper motion as initial conditions. In gray we draw random initial conditions from the corresponding posteriors. In the top two panels, we plot its trajectory in the X-Y and X-Z planes in Galactocentric coordinates. In the bottom panel, we plot a segment of the peculiar velocity as a function of time before the present. The rotated histogram on the right is the distribution of potential peculiar velocities at birth, inferred by sampling the trajectory at crossings of the Galactic plane that coincide (to within 10 Myr) with donor ages from our successful RLO2 binaries.
the onset of MT from the secondary onto the BH. We consider a successful RLO2 system to be any binary that evolves to simultaneously satisfy observational constraints on the BH and donor masses, donor effective temperature, and orbital period of J1305 to within 2σ of their observed values. We then use POSYDON to evolve a population of ZAMS binaries up until RLO2 while modeling and sampling over natal kick velocities, matching the results to our successful RLO2 systems and identifying potential J1305 progenitors.

The mass of the BH at RLO2 is constrained from above by the upper bound on the observed BH mass $M_{\text{BH,obs}} \leq 12.1\ M_\odot$. Meanwhile, the RLO2 period is constrained from below by the requirement that the donor is not already filling its RL at zero-age main sequence (ZAMS), and from above by the requirement that it will fill its RL in a Hubble time. With the exception of very low donor masses $M_{2,\text{RLO2}} \lesssim 0.75\ M_\odot$, this lower bound means that J1305’s orbit must have shrunk since RLO2. Since subsequent MT from the donor onto the BH would expand J1305’s orbit ($q < 1$), this is only possible with efficient magnetic braking. Assuming the companion stays tidally locked, spin angular momentum lost through magnetic braking would be compensated by the orbital angular momentum of the binary, shrinking its orbit. Since magnetic braking is inefficient in massive stars and at large periods, this adds the constraint that $M_{2,\text{RLO2}}$ is sufficiently small so that by the time it loses enough mass to enter the regime where magnetic braking is efficient, the period is still below the bifurcation period that delineates whether MT will grow or shrink the orbit in the presence of magnetic braking. We find that this effectively limits $M_{2,\text{RLO2}} < 3\ M_\odot$ and $P_{\text{RLO2}} < 1$ day.

From these constraints, we construct a grid of binaries—spaced uniformly in BH mass, donor mass, and orbital period at intervals of $1\ M_\odot$, $0.2\ M_\odot$, and 0.05 days, respectively—for which we calculate detailed MT sequences using MESA. Figure 2 shows results for selected slices of that grid. Of these sequences, we find 12—marked in colored shapes in Figure 2—that simultaneously satisfy observational constraints on the masses, period, and effective donor temperature of J1305 within 2σ. We refer to these as successful RLO2 binaries. We plot unsuccessful binaries that expanded throughout MT with gray circles and those below the bifurcation period that shrunk due to efficient magnetic braking with black circles. In Figure 3, we plot an example of a successful RLO2 MT sequence.

Having identified the space of potential J1305 progenitors at RLO2, we can continue to narrow down the potential space of J1305 progenitors at ZAMS. We begin by evolving a nominal population of 10,000,000 ZAMS binaries via POSYDON’s interpolation scheme over the MESA grids described in Fragos et al. (2023). We choose a population flat in mass ratio, with orbital separation sampled log-uniform between 5 and $10^4\ R_\odot$, and primary mass $M_{1,\text{ZAMS}}$ drawn from a Kroupa initial mass function (Kroupa 2001) between 7 and 120 $M_\odot$. It is reasonable to assume that J1305 did not undergo mass inversion and that $M_2$ will lose a negligible amount of mass between ZAMS and RLO2—consistent with predictions of negligible winds in low-mass stars—so we limit $M_{2,\text{ZAMS}} < 3\ M_\odot$ by the above argument that requires progenitors at RLO2 to be in a regime where magnetic braking is efficient. We evolve each binary until the core collapse of the primary (CC1), discarding systems that merged before compact object formation. Again assuming that $M_2$ will lose negligible mass before RLO2, we also discard any systems where the pre-SN donor mass $M_{2,\text{preSN}} > 3\ M_\odot$, leaving a population of $\sim 30,000$ pre-SN binaries that could viably be progenitors to J1305.

Finally we evolve the viable pre-SN binaries through CC1 and the subsequent detached binary evolution up until RLO2. Rather than assume any particular SN prescription, we take a broad, agnostic approach to modeling the core collapse, sampling mass loss uniformly such that the remnant BH mass is between the minimum and maximum of our winning RLO BH masses and natal kicks $V_{\text{kick}}$ uniformly between 0 and 500 km s$^{-1}$. We repeat this sampling 6000 times per binary, calculating the post-SN orbital properties and systemic velocities according to Kalogera (1996), and evolve the resulting BH + H-rich star binaries until the donor fills its RL at RLO2. We then identify potential J1305 progenitors from this population by matching them to the cells of our successful RLO2 binaries, forming $\sim 850$ potential evolutionary histories for J1305. We refer to these binaries as “potential progenitors.” We note that by sampling uniformly over mass loss and kick velocity at SN, our span of potential progenitors is conservative. We discuss our results and how we weigh them by the observed properties of J1305 in Section 3.3.

### 3.3. Constraints on the Natal BH Kick and Progenitor Properties

Since not all potential progenitors to J1305 are equally successful, we weigh the distributions over our potential progenitor parameters by the observed properties of J1305.

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8 While it is possible that J1305 entered RLO2 immediately after a CE phase or immediately post-SN due to a fortuitous kick, this becomes less likely when accounting for observations that find that the donor is evolved. Due to the high mass of the BH progenitor relative to the donor, this would make it unlikely that the donor began MT at such an early stage given we are still observing it with such a short period today.
That is, given a set of observable quantities $\theta_f$ at present-day corresponding to a progenitor binary with parameters $\theta_i$, $p(\theta_f | \theta_i)$ is weighted by the probability of the observable quantities given the electromagnetic data $EM$:

$$p(\theta_f | EM) \propto p(\theta_i) p(\theta_f | \theta_i | EM).$$

(1)

For $\theta_f \in \{M_{1,obs}, q_{obs}, T_{\text{eff,obs}}\}$ we use (asymmetric as appropriate) Gaussians to fit the corresponding posteriors reported in Sánchez et al. (2021). For $V_{\text{pec,birth,obs}}$, we use a kernel density estimation to fit the posterior shown in the bottom right panel of Figure 1. We plot the results in Figure 4. In blue we plot the unweighted posteriors, which is the set of binaries that at some point had a BH mass, mass ratio, and effective temperature within $2\sigma$ of the observed value. In green, orange, purple, and red we weight these posteriors individually according to the observed $V_{\text{pec,birth,obs}}, M_{1,obs}, q_{obs}$, and $T_{\text{eff,obs}}$. Our final results, in black, are obtained by multiplying all of the observational weights together. In Figure 5, we plot the final marginalized posterior over the pre-SN primary mass and kick velocity, weighted by all observations.

Although we allowed for arbitrarily high mass loss upon core collapse, we find that $\Delta M_{1,CC} < 0.9 M_\odot$ with 95% confidence. With low $\Delta M_{1,CC}$ the velocity imparted on the center of mass via mass loss alone would have been small, with $V_{\Delta M} = 0.7^{+1.0}_{-0.5}$ km s$^{-1}$. In the absence of an additional SN kick on the remnant BH, the systemic velocities would be incompatible with the inferred $V_{\text{pec,birth,obs}}$. Indeed, once weighted by observations—and crucially the kinematic constraints on the total birth velocity—we find that $V_{\text{kick}} > 70$ km s$^{-1}$ with 95% confidence, with $V_{\text{kick}} = 91^{+23}_{-12}$ km s$^{-1}$.

The presence of an SN kick may also have helped J1305 reach the short periods at RLO2 that we find to be necessary to produce it. Since the progenitor would have circularized during a CE phase, the post-SN orbit would have mild eccentricity—and therefore would have difficulty shedding angular momentum—in the absence of a kick and with little to no mass loss. Indeed, we find that all but the shortest-period pre-SN potential progenitors received a kick. Before weighting by the inferred $V_{\text{pec,birth}}$, we find that of the progenitors that received a kick of <10 km s$^{-1}$, all had pre-SN periods of <5 days, and none had post-SN eccentricities of >0.1.

We stress that these results should be understood as constraints inferred using flat priors and are therefore conservative. Our finding of a scenario with low mass loss and non-negligible natal kick are at odds with SN prescriptions that scale BH kicks by mass loss (Bray & Eldridge 2018; Giacobbo & Mapelli 2020) resulting in negligible kicks with low mass loss. On the other hand, simulations in Coleman & Burrows (2022)—listed in Table 1 and discussed in Section 3.1.3 therein—find that BHs may receive natal kicks of up to
and solid contours enclose central 68%, 90%, and 99% probabilities.

\( \approx 75 \text{ km s}^{-1} \) due to relativistic asymmetric neutrino emission alone, with negligible contribution from matter ejecta.

### 4. Conclusions

We find that MAXI J1305 is only the second BH system that—when analyzed in the context of both its kinematic and binary/stellar history under the assumption that it was formed in the Galactic disk via isolated binary evolution and assuming uninformative priors on the mass-loss and natal kick velocity imparted at SN—requires a natal kick to exist. Our inferred natal kick of \( 91^{+23}_{-12} \text{ km s}^{-1} \) is consistent with Sánchez et al. (2021), who estimated from kinematics alone that the total center-of-mass velocity imparted to this system was \( 75^{+25}_{-12} \text{ km s}^{-1} \). It is also consistent with Atri et al. (2019), who found that the population of BH LMXB birth velocities is well fit by a normal distribution peaking around \( 107 \text{ km s}^{-1} \) with a standard deviation of \( 16 \text{ km s}^{-1} \). Our result suggests that the birth velocity of J1305 could not have been provided by symmetric mass loss alone but requires an additional natal kick. Our 95% lower limit on this natal kick of \( 70 \text{ km s}^{-1} \) is also similar to the findings of Fragos et al. (2009) for XTE J1118+40, who found that its BH received a kick of at least \( 80 \text{ km s}^{-1} \). With this analysis of J1305, we strengthen the case that at least some BHs receive natal kicks at birth.

We find that our results are robust against kinematic uncertainties. The inferred boost to the center-of-mass velocity from symmetric mass loss alone, \( V_{\Delta M} = 0.7^{+1.5}_{-0.3} \text{ km s}^{-1} \), would be incompatible with even moderate birth peculiar velocities \( \geq 10 \text{ km s}^{-1} \). We assess that our inference is not qualitatively affected by our choice of Milky Way potential nor the assumption that J1305 was born exactly in the Galactic midplane with a circular velocity. Further, as shown in Fragos et al. (2009) for a system with a very similar donor, the kick constraints are not sensitive to the assumed magnetic braking law. We do note that, as in all binary evolution calculations to date, we assume that binaries instantly circularize upon the onset of MT. This is not always a well-justified assumption, and it leads to a mismatch between the donor ages produced in our population synthesis and in our individual MESA runs that matched the observed properties; it is possible that correcting for this effect (K. Rocha et al. 2023, in preparation) may have a small quantitative effect on our kick constraints. Lastly, we note that at \( \sim 1 \text{ kpc} \) above the Galactic midplane, we cannot exclude that J1305 formed dynamically before being ejected from a globular cluster, in which case our analysis is not applicable.

Through this and other past studies we have demonstrated that, accounting for all observational characteristics and coupling binary evolution and kinematic modeling, we can provide robust constraints on natal BH kicks and associated mass loss at formation. With an increasing sample of LMXBs with proper motion and radial velocity estimates, our goal in future work is to investigate potential statistical correlations between BH kicks and mass-loss characteristics at birth, which may shed light on the natal kick mechanism.

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**Software:** NumPy (van der Walt et al. 2011), SciPy (Virtanen et al. 2020), matplotlib (Hunter 2007), pandas (Wes McKinney 2010), POGSYDION (Fragos et al. 2023).

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