Proportionality Between Peak Optical Luminosity & Orbital Period of Stellar-Mass Black Hole Candidates

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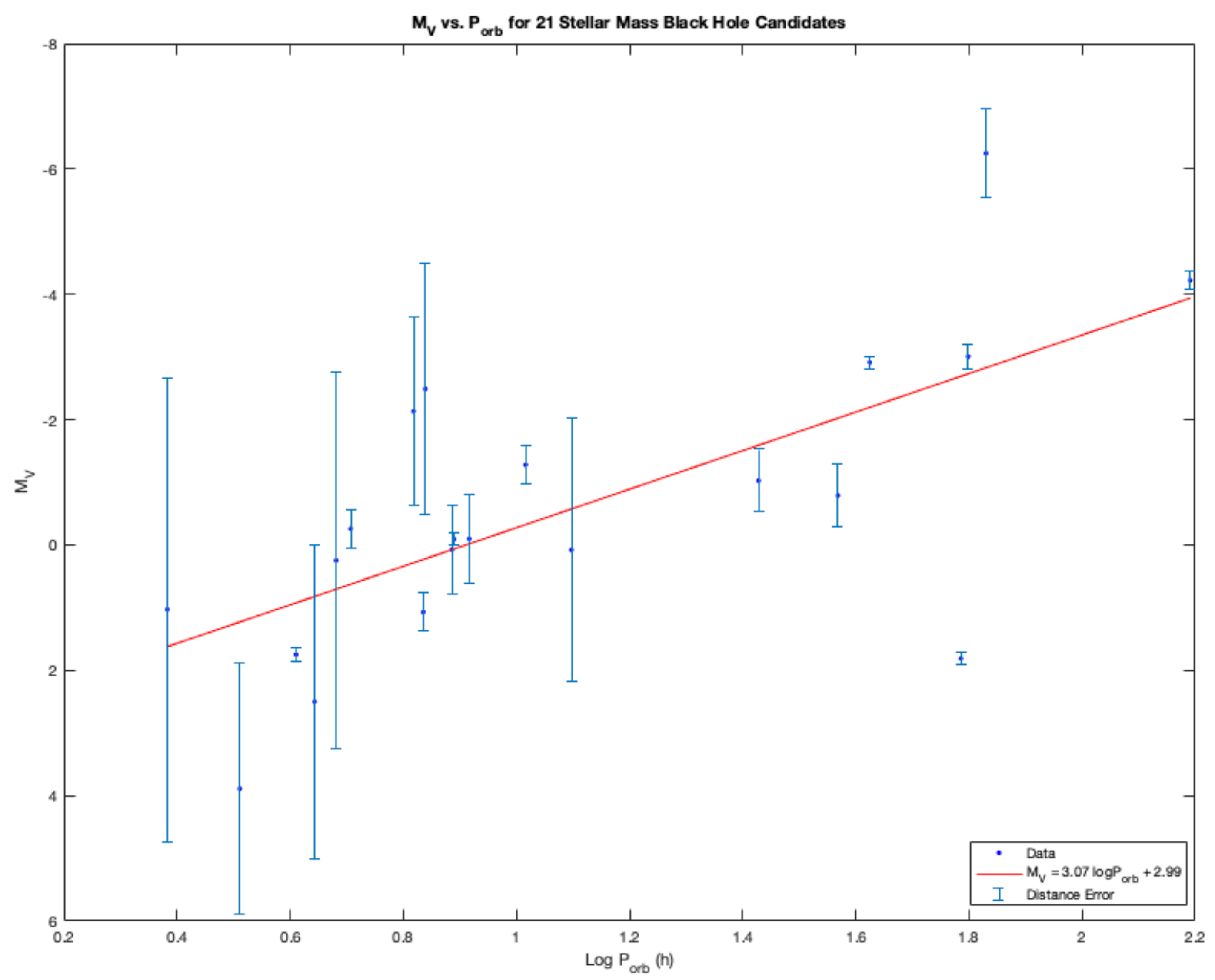
Abstract

We compare the peak optical luminosity with the orbital period for a sample of 21 stellar-mass black hole candidates with good measurements of both quantities. We find that the peak absolute magnitude for the outbursts follows a relation with $M_V = 3.07logP + 2.99$ which aligns closely with an $L_V \propto P^{7/6}$ relation. This is a similar relationship to that found for cataclysmic variables. We discuss the implications of these results for finding black hole X-ray binaries in other galaxies and in our own Galaxy with the Large Synoptic Survey Telescope and with other future large time domain surveys.

Introduction

In utilizing previously logged data (Corral-Santana et al. 2016) of the 60 presently-known stellar-mass black hole X-ray binaries in our Galaxy, we observe the general relationship between their absolute magnitudes and orbital periods and draw a strong correlation between black hole binary orbital period and peak optical luminosity. A similar project completed by T. Shabbaz & E. Kuulkers (1997) was carried out to find a correlation between optical outburst amplitude and orbital period of soft X-ray transients. Approximately 20 years since Shabbaz-Kuulkers (1997), we now discuss the implications of a similar relationship: The proportionality between peak optical luminosity and orbital period of a sample of 21 stellar mass black hole candidates. As we approach the completion of the Large Synoptic Survey Telescope (LSST), we expect that with the discovery of similar extragalactic x-ray black hole binaries, we will be able to revisit this model with more data which may further strengthen the observed relationship and potentially bring to our attention outliers observed to be stellar-mass black hole binaries that may not actually fit this mold.



Object ID	m	$E(B-V)$ [a]	M [b]	$Log(P)$ (hr) [c]	d (kpc)
4U 1543-475 IL Lup	14.9	0.5	-1.03	1.43	7.5 ± 0.5
4U 1755-338 V4134 Sgr	18.5	0.62	2.50	0.64	6.5 ± 2.5
1H 1659-487 GX 339-4 = V821 Ara	14.7	1.2	-2.91	1.62	>6
3A 0620-003 N Mon 1975 = V616 Mon	11.1	0.35	-.09	0.09	1.1 ± 0.1
H 1705-250 N Oph 1977 = V2107 Oph	B= 16.3	0.5	0.08	1.09	8.6 ± 2.1
GS 1354-64 BW Cir	16.9	1.00	1.81	1.79	25
GS 2000+251QZ Vul	16.4	1.4	-.09	0.92	2.7 ± 0.7
GS 2023+338 V404 Cyg	11.7	1.3	-4.22	2.19	2.4 ± 0.14
GRS 1124-684 N Mus 1991 = GU Mus	13.5	0.3	-1.28	1.02	5.9 ± 0.3
GRO J0422+32 V518 Per	R= 12.7	0.3	-.26	0.71	2.5 ± 0.3
GRS 1009-45 N Vel 1993 = MM Vel	R= 14.6	0.21	1.07	0.84	3.8 ± 0.3
GRO J1655-40 N Sco 1994 = V1033 Sco	R= 13.6	1.3	-3.01	1.80	3.2 ± 0.2
XTE J1550-564 V381 Nor	16.6	1.33	-0.79	1.57	4.5 ± 0.5
SAX J1819.3-2525 V4641 Sgr	8.80	0.35	-6.25	1.83	6.2 ± 0.7
XTE J1859+226 V406 Vul	R= 15.5	0.58	-2.13	0.82	12.5 ± 1.5
XTE J1118+480KV UMa	13.0	0.02	1.75	0.61	1.7 ± 0.1
XTE J1650-500	B= 16.8	1.50	0.08	0.89	2.6 ± 0.7
SWIFT J1753.5-0127	R= 15.9	0.45	3.89	0.51	6 ± 2
XTE J1752-223 V5678 Sgr	J= 15.8	1.40	-2.49	0.84	6 ± 2
MAXI J1659-152 V2862 Oph	16.78	0.34	1.03	0.38	8.6 ± 3.7
MAXI J1836-194	16.33	0.6	0.24	0.68	7 ± 3

[a] Correction factors from Corral-Santana et al. (2016).
[b] Derived using $E(B-V)$ value and eqs. (2) & (3).
[c] Logarithms of P from Corral-Santana (2016).

Discussion of Method

Using data from the Corral-Santana et al. stellar-mass black hole catalog, BlackCAT, we performed our data analysis based on 21 stellar-mass black hole candidates' outburst magnitudes and orbital periods. Candidates whose outbursts magnitudes were not observed in the V-band were converted to V, and we accounted for reddening in all absolute magnitude calculations using A_V values from a Vega-AB magnitude conversion chart. We plotted the orbital period against each absolute magnitude value and fit the data linearly, which we found to correspond to the equation $M_V = 3.07logP + 2.99$. In determining how our fit equation correlated to a model of the proportionality between peak optical luminosity and period, we related the x-ray luminosity to both the orbital period and the product of the optical luminosity and the outer radius R of the black hole's accretion disk and, by application of Kepler's 3rd law, determined a formula for the semi-major axis of orbit in relation to the total black hole mass and period (assuming the formula to be true if the particular black hole in question were moved to a distance of 1 AU away). Under the further assumption that the semi-major axis of orbit is proportional to the accretion disk's outer radius R, the proportionality between optical and x-ray luminosity could then be rewritten in terms of the semi-major axis 'a'. Expanding the right hand side of this proportionality and substituting for the x-ray luminosity, we reached the 7th line of the model in which optical luminosity is proportional to the orbital period and black hole mass. Our final line is the reduced version of the same proportionality (given that the total black hole mass disappears from this relation due to our neglecting the weak dependence on system mass).

$L_X \propto P_{orb}$

(X-ray luminosity ∝ orbital period)

$L_V \propto L_X^{1/2} R$

(Optical luminosity ∝ product of X-ray luminosity and outer accretion disk radius)

$P_{orb} \propto a^3$

(Orbital period ∝ semi-major axis of orbit)

$a = 1\ AU (\frac{M_{tot}}{M_\odot})^{1/3} (\frac{P_{orb}}{yr})^{2/3}$

('a' expanded in terms of BH mass and period)

$R \propto a$

(Outer radius of black hole accretion disk ∝semi-major axis of orbit)

$L_V \propto L_X^{1/2} a$

(Optical luminosity ∝ product of X-ray luminosity and semi-major axis 'a')

$L_V \propto (P_{orb})^{1/2} (M_{tot})^{1/3} (P_{orb})^{2/3}$

(Optical luminosity ∝ product of orbital period and total mass)

$L_V \propto P^{7/6}$

(Final proportionality between optical luminosity and orbital period)

Results

Upon plotting the relationship between absolute magnitude and orbital period, we determined our linear fit, $M_V = 3.07logP + 2.99$ to be a good comparison to our proportionality between peak optical luminosity and orbital period which, based on the model introduced in Paradjis/Mclintock (1985), we found to be $L_V \propto P^{7/6}$. This 7/6 is approximately a 0.6 difference from the corresponding factor we drew from our fit equation. Specifically, $L_V \propto P_{orb}^{1.228}$ (based on our linear fit) & $L_V \propto P_{orb}^{1.167}$ (based on the proportionality model).

Based on these results it is confirmed that our objects do, in fact, fit the general assumption that the longer the orbital period, the brighter their absolute magnitudes– and thus their luminosities– are expected to be. However, our data set contains two outliers, V4164 Sgr, whose absolute magnitude appears to be significantly brighter than expected given its log period of 0.64 hours and BW Cir, whose absolute magnitude is much lower than the fit predicts given its log period of 1.79 hours. We predict that the inconsistency in V4164 may likely be due to to the fact that it is a late B type-star, and potentially an early A type, resulting in the possibility of its properties behaving radically differently from other x-ray binary transients. As for BW Cir, we consider the possibility that its donor star may not quite be Roche-lobe filling, producing x-ray outbursts of fainter magnitude.

Conclusion

We find that the proportionality between peak optical luminosity and orbital period of our stellar-mass black hole sample correlates closely with the linear fit $M_V = 3.07logP + 2.99$ from our Absolute Visual Magnitude-Orbital Period plot. With only a 0.6 difference between our orbital period factor, and the corresponding absolute visual magnitude factor, we conclude that this sample fits generally well with the proportionality model. Ideally, within the next few years, the Large Synoptic Survey Telescope will allow us to acquire more data for similar black hole x-ray binaries in the Milky Way and in other nearby galaxies, such as M31, which we will be able to apply to this model. The construction of the LSST will greatly increase the possibility of finding black hole X-ray binaries of this same size-class, as its projected goal is to survey the entire available sky every few nights. The data presented serves as documentation of a conclusion drawn from a sample of known stellar-mass X-ray binaries and will become comparable to new data as more binaries like these may soon be discovered.

References

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